# Tight Last-Iterate Convergence of the Extragradient and the Optimistic Gradient Descent-Ascent Algorithm for Constrained Monotone Variational Inequalities 

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#### Abstract

The monotone variational inequality is a central problem in mathematical programming that unifies and generalizes many important settings such as smooth convex optimization, twoplayer zero-sum games, convex-concave saddle point problems, etc. The extragradient algorithm by Korpelevich [1976] and the optimistic gradient descent-ascent algorithm by Popov [1980] are arguably the two most classical and popular methods for solving monotone variational inequalities. Despite their long histories, the following major problem remains open. What is the last-iterate convergence rate of the extragradient algorithm or the optimistic gradient descent-ascent algorithm for monotone and Lipschitz variational inequalities with constraints? We resolve this open problem by showing that both the extragradient algorithm and the optimistic gradient descent-ascent algorithm have a tight $O\left(\frac{1}{\sqrt{T}}\right)$ last-iterate convergence rate for arbitrary convex feasible sets, which matches the lower bound by Golowich et al. [2020a,b]. Our rate is measured in terms of the standard gap function. At the core of our results lies a non-standard performance measure - the tangent residual, which can be viewed as an adaptation of the norm of the operator that takes the local constraints into account. We use the tangent residual (or a slight variation of the tangent residual) as the the potential function in our analysis of the extragradient algorithm (or the optimistic gradient descent-ascent algorithm) and prove that it is non-increasing between two consecutive iterates.


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## 1 Introduction

The monotone variational inequality (VI) problem plays a crucial role in mathematical programming, providing a unifying setting for the study of optimization and equilibrium problems. It also serves as a computational framework for numerous important applications in fields such as Economics, Engineering, and Finance [Facchinei and Pang, 2007]. Monotone VIs have been studied since the 1960s [Hartman and Stampacchia, 1966, Browder, 1965, Lions and Stampacchia, 1967, Brezis and Sibony, 1968, Sibony, 1970]. Formally, a monotone VI is specified by a closed convex set $\mathcal{Z} \subseteq \mathbb{R}^{n}$ and a monotone operator $F: \mathcal{Z} \rightarrow \mathbb{R}^{n},{ }^{1}$ with the goal of finding a $z^{*} \in \mathcal{Z}$ such that

$$
\begin{equation*}
\left\langle F\left(z^{*}\right), z^{*}-z\right\rangle \leq 0 \quad \forall z \in \mathcal{Z} . \tag{1}
\end{equation*}
$$

We further assume the operator $F$ to be Lipschitz, which is a natural assumption that is satisfied in most applications and is also made in the majority of algorithmic works concerning monotone VIs. An important special case of the monotone and Lipschitz VI is the convex-concave saddle point problem:

$$
\begin{equation*}
\min _{x \in \mathcal{X}} \max _{y \in \mathcal{Y}} f(x, y) \tag{2}
\end{equation*}
$$

where $\mathcal{X}$ and $\mathcal{Y}$ are closed convex sets in $\mathbb{R}^{n}$, and $f(\cdot, \cdot)$ is smooth, convex in $x$, and concave in $y .{ }^{2}$ Besides its central importance in Game Theory, Convex Optimization, and Online Learning, the convex-concave saddle point problem has recently received a lot of attention from the machine learning community due to several novel applications such as the generative adversarial networks (GANS) (e.g., [Goodfellow et al., 2014, Arjovsky et al., 2017]), adversarial examples (e.g., [Madry et al., 2018]), robust optimization (e.g., [Ben-Tal et al., 2009]), and reinforcement learning (e.g., [Du et al., 2017, Dai et al., 2018]).

The extragradient (EG) algorithm by Korpelevich [1976] and the optimistic gradient descentascent (OGDA) algorithm by Popov [1980] are arguably the two most classical and popular methods for solving Lipschitz and monotone VIs. Interestingly, a fundamental property of these two simple and natural algorithms remained elusive despite their long histories. Namely, the last-iterates of both algorithms are only known to asymptotically converge to a solution of the monotone and Lipschitz VI, ${ }^{3}$ but no upper bounds on the rate of convergence had been provided for general settings. Motivated by this gap of our understanding, the following question has been posed as an open question in several recent works [Wei et al., 2021b, Golowich et al., 2020b,a, Hsieh et al., 2019].

What is the last-iterate convergence rate of the extragradient algorithm and the optimistic gradient descent-ascent algorithm for monotone and Lipschitz variational inequalities with constraints?

[^1]We resolve this open problem by providing the tight last-iterate convergence rate of EG and OGDA under arbitrary convex constraints. Indeed, the same problem has not been answered even for two-player zero-sum games, arguably one of the most basic monotone and Lipschitz VIs. ${ }^{4}$ Prior to our work, the only setting where an upper bound on the rate of convergence exists for either EG or OGDA for solving general Lipschitz and monotone VIs is when the problem is unconstrained, i.e., $\mathcal{Z}=\mathbb{R}^{n}$, [Golowich et al., 2020b, Gorbunov et al., 2021, Golowich et al., 2020a].

Main Result: For any monotone and Lipschitz variational inequality problem with an arbitrary convex constraint set $\mathcal{Z}$, both EG and OGDA with constant step size achieve a tight last-iterate convergence of $O\left(\frac{1}{\sqrt{T}}\right)$ in terms of the standard convergence measures - the gap function (Definition 1) and the tangent residual (Definition 3). ${ }^{a}$ See Theorem 3 for the formal statement. We further show that the tangent residual is an upper bound of the natural residual (Lemma 1), so our result also implies a tight last-iterate convergence rate of $O\left(\frac{1}{\sqrt{T}}\right)$ for the natural residual.

[^2]Our upper bounds in terms of the gap function and the natural residual match the lower bounds of Golowich et al. [2020b,a], that is, they match in all of the following terms: T, the Lipschitz constant of $F$, and the distance between the starting point $z_{0}$ and the solution $z^{*}$.

To the best of our knowledge, our result is the first to provide a last-iterate convergence rate for solving monotone and Lipschitz VIs using any algorithm that belongs to the general class known as p-stationary canonical linear iterative algorithms (p-SCLI) [Arjevani and Shamir, 2016], which contains the EG, OGDA, and other well-known algorithms. Although often viewed as an approximation to EG, OGDA has an additional feature compared to EG, i.e., it is a no-regret learning algorithm (see e.g., [Rakhlin and Sridharan, 2013]). A nice implication of our result for OGDA is that for smooth and monotone games (see Appendix A for the definition), players can each play a no-regret learning algorithm, i.e., OGDA, with constant learning rate, and the overall player behavior exhibits $O\left(\frac{1}{\sqrt{T}}\right)$ last-iterate convergence rate to a Nash equilibrium in terms of the gap function.

Why Last-Iterate Convergence? Both the EG and OGDA algorithms are known to have averageiterate convergence. In particular, the average of the iterates of the algorithm converges at a rate of $O(1 / T)$ [Nemirovski, 2004, Auslender and Teboulle, 2005, Tseng, 2008, Monteiro and Svaiter, 2010, Mokhtari et al., 2020, Hsieh et al., 2019]. Nonetheless, there are several important reasons to study last-iterate convergence. First, not only is last-iterate convergence theoretically stronger and more appealing, it is also the only type of convergence that describes the trajectory of an algorithm. As demonstrated by Mertikopoulos et al. [2018], the trajectory of an algorithm may be cycling around in the space perpetually while still converges in the average-iterate sense. In game theory,

[^3]we often view these algorithms as models of agents' behavior in a system/game. Thus, only lastiterate convergence provides a description of the evolution of the system. Additionally, EG and OGDA have been successfully applied to improve the training dynamics in GANs, as the training of GANs can be formulated as a saddle point problem [Daskalakis et al., 2018, Yadav et al., 2018, Liang and Stokes, 2019, Gidel et al., 2019a,b, Chavdarova et al., 2019]. On the one hand, in this formulation of GANs, the objective function $f$ is usually non-convex and non-concave, making existing theoretical guarantees for the average iterate inapplicable. On the other hand, the last iterate typically has good performance in practice. Thus, it is crucial to develop machinery that allows us to analyze the behavior of the last iterate of these algorithms.

### 1.1 Our Performance Measure: the Tangent Residual

A major challenge we face for establishing the last-iterate convergence for EG or OGDA in the constrained setting is the choice of the convergence measure. For simplicity, we focus on our choice of the performance measure for EG, as our performance measure for OGDA is similar and inspired by our performance measure for EG. In the unconstrained case, the central performance measure for EG is the norm of the operator. The key component in both [Golowich et al., 2020b] and [Gorbunov et al., 2021] is to establish that the norm of the operator at the last iterate (also the $T$-th iterate) is upper bounded by $O\left(\frac{1}{\sqrt{T}}\right)$, which implies a $O\left(\frac{1}{\sqrt{T}}\right)$ last-iterate convergence rate for the gap function.

In the constrained setting, the norm of the operator is a poor choice to measure convergence, as it can be far away from 0 even in the limit, and is hence insufficient to guarantee convergence in terms of the gap function. A standard generalization of the norm of the operator in the constrained setting is the natural residual (Definition 4), which takes the constraints into account and is guaranteed to converge to 0 in the limit. Unfortunately, we observe that the natural residual is not monotonically decreasing even in basic bilinear games (see Appendix D), making it difficult to directly analyze. Similar non-monotonicity has been observed for several other natural performance measures such as the norm of the operator mapping introduced in [Diakonikolas, 2020] and the gap function, leaving all these performance measures unsuitable. See more discussion about these performance measures in Section 3 and Appendix D.

We choose a non-standard performance measure: the tangent residual, which can be viewed as the norm of the operator projected to the tangent cone of the current iterate (Definition 3). To the best of our knowledge, this performance measure has not been used in the study of EG or OGDA. The tangent residual plays a crucial role in our analyses for both algorithms. Unlike the aforementioned performance measures, we show that the tangent residual is monotonically decreasing and has a last-iterate convergence rate of $O\left(\frac{1}{\sqrt{T}}\right)$ for EG. For OGDA, we prove that a small modification of the tangent residual is monotonically decreasing, which implies that the tangent residual has a last-iterate convergence rate of $O\left(\frac{1}{\sqrt{T}}\right)$. Using the convergence rate of the tangent residual, we can easily derive the last-iterate convergence rate of other classical performance measures such as the natural residual or the gap function. However, we suspect these rates can be challenging to obtain directly.

### 1.2 Sum-of-Squares based Analysis

We provide a quick overview on how we establish the monotonicity of the tangent residual of the EG algorithm. We first introduce the concept of sum-of-squares programming.

Sum-of-Squares (SOS) Programming. Suppose we want to prove that a polynomial $p(x) \in$ $\mathbb{R}\left[x_{1}, \ldots, x_{n}\right]$ is non-negative over a semialgebraic set $\mathcal{S}=\left\{x \in \mathbb{R}^{n}: g_{i}(x) \leq 0, \forall i \in[m]\right\}$, where each $g_{i}(x)$ is also a polynomial. One way is to construct a certificate of non-negativity, for example, by providing a set of nonnegative coefficients $\left\{a_{i}\right\}_{i \in[m]} \in \mathbb{R}_{\geq 0}^{m}$ such that $p(x)+\sum_{i \in[m]} a_{i}$. $g_{i}(x)$ is a sum-of-squares polynomial, that is, a polynomial that can be expressed as the sum of squares of further polynomials. Surprisingly, if $p(x)$ is indeed non-negative over $\mathcal{S}$, a certificate of non-negativity always exists as guaranteed by a foundational result in real algebraic geometry - the Krivine-Stengle Positivestellensatz [Krivine, 1964, Stengle, 1974], a generalization of Artin's resolution of Hilbert's 17th problem [Artin, 1927]. Note that, it is sometimes necessary to allow more sophisticated forms of certificates than in the example above, e.g., replacing each coefficient $a_{i}$ with a SOS polynomial $s_{i}(x)$, etc. The complexity of a certificate is parametrized by the highest degree of the polynomial involved. The SOS programming consists of a hierarchy of algorithms, where the $d$-th hierarchy is an algorithm that searches for a certificate of non-negativity up to degree $2 d$ based on semidefinite programming.

We mainly discuss the analysis of EG here, as the analysis of OGDA is similar and also based on SOS programming. At the core of our analysis of the EG algorithm lies the monotonicity of the squared tangent residual, which can be formulated as the non-negativity of a degree-4 polynomial in the iterates. ${ }^{5}$ Our original proof directly applies SOS programming to certify the non-negativity of this degree-4 polynomial. The certificate is rather complex and involves a polynomial identity of a degree- 8 polynomial in 27 variables, which we discover by solving a degree- 8 SOS program. Interested readers can find the proof in Appendix F. In this version, we include a simplified proof. By introducing auxiliary vectors that are not part of the update rule of EG, we provide an equivalent formulation of the squared tangent residual (Lemma 6) that is a degree-2 polynomial, which allows us to prove the monotonicity of the squared tangent residual using a degree-2 SOS program. The proof can be found in Section 5.2.

For OGDA, we are not able to show that the squared tangent residual is monotone. Inspired by the adaptive potential proof in [Golowich et al., 2020a], we suspect that some extra correction term is needed to construct the potential function. Instead of trying to devise such a correction term manually, we manage to directly find one by searching over a family of performance measures using SOS programming. The search we perform is heuristic but might be helpful to discover potential functions in other problems. See Section 6 for a more detailed discussion.

### 1.3 Related Work

Last-Iterate Convergence Rate for EG-like Algorithms in the Unconstrained Setting. Golowich et al. [2020b,a] show a lower bound of $\Omega\left(\frac{1}{\sqrt{T}}\right)$ for solving bilinear games using any p-

[^4]SCLI algorithms, which include EG and OGDA. For EG, Golowich et al. [2020b] show an matching upper bound under an additional second-order smoothness condition. Gorbunov et al. [2021] improve the result and show that the same upper bound holds without the second-order smoothness condition. For OGDA, Golowich et al. [2020a] provides a matching upper bound under the same second-order smoothness condition. These upper bounds hold for all smooth and Lipschitz VIs. With the additional assumption that the operator $F$ is cocoercive, Lin et al. [2020] show a $O\left(\frac{1}{\sqrt{T}}\right)$ convergence rate for online gradient descent. If we further assume that either $F$ is strongly monotone in VI or the payoff matrix $A$ in a bilinear game has all singular values bounded away from 0 , linear convergence rate is known for EG, OGDA, and several of their variants [Daskalakis et al., 2018, Gidel et al., 2019a, Liang and Stokes, 2019, Mokhtari et al., 2020, Peng et al., 2020, Zhang and Yu, 2020].

Last-Iterate Convergence Rate for EG-like Algorithms in the Constrained Setting. The results for the constrained setting are sparser. If the operator $F$ is strongly monotone, we know that EG and some of its variants have linear convergence rate [Tseng, 1995, Malitsky, 2015]. Several papers establish the asymptotic convergence, i.e., converge in the limit, of the optimistic multiplicative weight updates in constrained convex-concave saddle point problems [Daskalakis and Panageas, 2019, Lei et al., 2021]. Finally, a recent paper by Wei et al. [2021b] provides a linear rate convergence of OGDA for bilinear games when the domain is a polytope. They show that there is a problem dependent constant $0<c<1$ that depends on the payoff matrix of the game as well as the constraint set, so that the error shrinks by a $1-c$ factor. However, $c$ may be arbitrarily close to 0 , even if we assume the corresponding operator to be $L$-Lipschitz. As a result, their convergence rate is slower than ours when $T$ is not comparable to $\frac{1}{c}$, which may be exponentially large in the dimension $n$, though their rate will eventually catch up. Overall, their "instance-specific" bound is incomparable and complements the worst-case view taken in this paper, where we want to derive the worstcase convergence rate for all VIs with monotone and $L$-Lipschitz operator $F$. Our result is the first last-iterate convergence rate in this worst-case view and matches the lower bound by Golowich et al. [2020b,a].

Other Algorithms and Performance Measures. Other than the gap function, one can also measure the convergence using the norm of the operator if the setting is unconstrained, or the natural residual (Definition 4) or similar notions if the setting is constrained. In the unconstrained setting, Kim [2021], Yoon and Ryu [2021], and Lee and Kim [2021] provide algorithms that obtain $O\left(\frac{1}{T}\right)$ convergence rate in terms of the norm of the operator, which is shown to be optimal by Yoon and Ryu [2021] for Lipschitz and monotone VIs. In the constrained setting, Diakonikolas [2020] shows the same $O\left(\frac{1}{T}\right)$ convergence rate under the extra assumption that the operator is cocoercive and loses an additional logarithmic factor when the operator is only monotone. Our result implies a $O\left(\frac{1}{\sqrt{T}}\right)$ last-iterate convergence rate in terms of the natural residual for both EG and OGDA. From an optimization point of view, i.e., the goal is to solve a Lipschitz and monotone VI, we should choose one of the above faster algorithms over EG or OGDA. However, one of our main motivation is game theoretic, that is, we would like to view simple algorithms such as OGDA and EG as models of agents' behavior and understand the speed for the overall behavior
to converge to a Nash equilibrium. From this game-theoretic view point, we believe understanding the last-iterate convergence rate of simple algorithms such as EG and OGDA is an important question.

Computer-Aided Proofs. A powerful computer-aided proof framework - the performance estimation problem (PEP) technique (e.g., [Drori and Teboulle, 2014, Taylor et al., 2017b]) is widely applied to analyze first-order iterative methods. Indeed, the last-iterate convergence rate of EG in the unconstrained setting by Gorbunov et al. [2021] is obtained via the PEP technique. Although the PEP framework can handle projections [Taylor et al., 2017a, Ryu et al., 2020, Goujaud et al., 2022, Dragomir et al., 2021], the main challenge for applying it to the constrained setting is that, the PEP framework requires the performance measures to be polynomials of degree 2 or less (see e.g., [Taylor et al., 2017a]). ${ }^{6}$ In fact, solving the PEP is equivalent to solving a degree-2 SOS program, which can be viewed as the dual of the PEP [Tan et al., 2021]. In the unconstrained setting, the performance measure is a degree-2 polynomial - the squared norm of the operator, and that is why one can either use the PEP (as in [Gorbunov et al., 2021]) or a degree-2 SOS to certify its monotonicity (Theorem 1). In the constrained setting, we use the squared tangent residual to measure the algorithm's progress, which in our original formulation is a degree 4 polynomial, making the PEP framework not directly applicable. ${ }^{7}$ As the SOS approach can accommodate polynomial objectives and constraints of any degree, we could directly apply it to certify the monotonicity of the tangent residual in the constrained setting, although the resulting proof is complex. With the new formulation of the squared tangent residual (Lemma 6), we manage to simplify our proof and derive it using a degree-2 SOS program. It is also not hard to see that one can apply the PEP framework on the new formulation of the squared tangent residual, and the resulting program is the dual program of our degree-2 SOS program. We believe an interesting future direction is to understand whether there are natural settings in optimization where degree-2 SOS programs are provably insufficient and higher degree SOS programs are necessary.

Lessard et al. [2016] analyze first-order iterative algorithms for convex optimization using a technique inspired by the stability analysis from control theory. They model first-order iterative algorithms using discrete-time dynamical systems and search over quadratic potential functions that satisfy a set of Integral Quadratic Constraints (IQC). Zhang et al. [2021] extend the IQC framework to study smooth and strongly monotone VIs in the unconstrained setting.

SOS Programming and Analysis of Iterative Methods. SOS programming has been employed in the design and analysis of algorithms in convex optimization. To the best of our knowledge, these results only concern minimization of smooth and strongly-convex functions in the unconstrained setting. Fazlyab et al. [2018] propose a framework to search the optimal parameters of the algorithm, e.g., step size. They use SOS programming to search over quadratic potential functions and parameters of the algorithm with the goal of optimizing the exponential decay rate of the

[^5]potential function. Tan et al. [2021] proposes to use SOS programming to study the convergence rates of first-order methods in unconstrained convex optimization.

Simultaneous Result on Last-Iterate Convergence of OGDA in the Unconstrained Setting. Shortly after we obtained the last-iterate convergence rate for OGDA in the constrained setting, we learned in early March, 2022 from private communication that Eduard Gorbunov, Gauthier Gidel, and Adrien Taylor had been working on the same problem. At the time of the communication, they could obtain the same last-iterate convergence rate for OGDA in the unconstrained case using a different method based on PEP.

## 2 Preliminaries

We consider the Euclidean Space $\left(\mathbb{R}^{n},\|\cdot\|\right)$, where $\|\cdot\|$ is the $\ell_{2}$ norm and $\langle\cdot, \cdot\rangle$ denotes inner product on $\mathbb{R}^{n}$. We use $z[i]$ to denote the $i$-th coordinate of $z \in \mathbb{R}^{n}$ and $e_{i}$ to denote the unit vector such that $e_{i}[j]:=\mathbb{1}[i=j]$, the dimension of $e_{i}$ is going to be clear from context.

Variational Inequality. Given a closed convex set $\mathcal{Z} \subseteq \mathbb{R}^{n}$ and an operator $F: \mathcal{Z} \rightarrow \mathbb{R}^{n}$, a variational inequality problem is defined as follows: find $z^{*} \in \mathcal{Z}$ such that

$$
\begin{equation*}
\left\langle F\left(z^{*}\right), z^{*}-z\right\rangle \leq 0 \quad \forall z \in \mathcal{Z} . \tag{3}
\end{equation*}
$$

We say $F$ is monotone if $\left\langle F(z)-F\left(z^{\prime}\right), z-z^{\prime}\right\rangle \geq 0$, for all $z, z^{\prime} \in \mathcal{Z}$, and is L-Lipschitz if, $\left\|F(z)-F\left(z^{\prime}\right)\right\| \leq L\left\|z-z^{\prime}\right\|$ for all $z, z^{\prime} \in \mathcal{Z}$.

Remark 1. One sufficient condition for such a $z^{*}$ to exist is when the set $\mathcal{Z}$ is bounded, but there are also other sufficient conditions that apply to unbounded $\mathcal{Z}$. See [Facchinei and Pang, 2007] for more details. Throughout this paper, we only consider monotone VIs that have a solution.

Definition 1 (Gap Function). A standard way to measure the performance of $z \in \mathcal{Z}$ is by its gap function defined as $\operatorname{GAP}_{\mathcal{Z}, F, D}(z)=\max _{z^{\prime} \in \mathcal{Z} \cap \mathcal{B}(z, D)}\left\langle F(z), z-z^{\prime}\right\rangle$, where $D>0$ is a fixed parameter and $\mathcal{B}(z, D)$ is a ball with radius $D$ centered at $z .{ }^{8}$ When $\mathcal{Z}, F$ and $D$ are clear from context, we omit the subscripts and write the gap function at $z$ as $\operatorname{GAP}(z)$.

The Extragradient Algorithm. Let $z_{k}$ be the $k$-th iterate of the Extragradient (EG) Algorithm. The update rule of EG is as follows:

$$
\begin{align*}
z_{k+\frac{1}{2}} & =\Pi_{\mathcal{Z}}\left[z_{k}-\eta F\left(z_{k}\right)\right]=\arg \min _{z \in \mathcal{Z}}\left\|z-\left(z_{k}-\eta F\left(z_{k}\right)\right)\right\|,  \tag{4}\\
z_{k+1} & =\Pi_{\mathcal{Z}}\left[z_{k}-\eta F\left(z_{k+\frac{1}{2}}\right)\right]=\arg \min _{z \in \mathcal{Z}}\left\|z-\left(z_{k}-\eta F\left(z_{k+\frac{1}{2}}\right)\right)\right\| . \tag{5}
\end{align*}
$$

[^6]The Optimistic Gradient Descent-Ascent Algorithm. Let $z_{k}$ and $w_{k}$ be the $k$-th iterate of the Optimistic Gradient Descent Ascent Method (OGDA) method. Let $z_{0}, w_{0}$ be arbitrary starting points in $\mathcal{Z}$. The update rule is as follows:

$$
\begin{align*}
w_{k+1} & =\Pi_{\mathcal{Z}}\left[z_{k}-\eta F\left(w_{k}\right)\right]=\arg \min _{z \in \mathcal{Z}}\left\|z-\left(z_{k}-\eta F\left(w_{k}\right)\right)\right\|  \tag{6}\\
z_{k+1} & =\Pi_{\mathcal{Z}}\left[z_{k}-\eta F\left(w_{k+1}\right)\right]=\arg \min _{z \in \mathcal{Z}}\left\|z-\left(z_{k}-\eta F\left(w_{k+1}\right)\right)\right\| \tag{7}
\end{align*}
$$

Note that the OGDA method only requires $T$ queries to the operator at $\left\{w_{k}\right\}_{0 \leq k \leq T-1}$, while EG requires $2 T$ queries to the operator. Additionally, OGDA is a more natural algorithm in multiagent online learning settings [Cesa-Bianchi and Lugosi, 2006, Shalev-Shwartz et al., 2012], as players play according to the strategy profile $w_{k}$ and receive gradient feedback $F\left(w_{k}\right)$ to compute $z_{k}$ and $w_{k+1}$, while EG requires players to play every half step $z_{k}$ and $z_{k+\frac{1}{2}}$ to get gradient feedback. Finally, as we mentioned before, OGDA is a no-regret algorithm while EG is not.

In Section 4 and 5, we present the analysis of the EG algorithm and provide a detailed description about how to use SOS programming to derive the proof. The analysis of the OGDA algorithm is a simple extension of our analysis to the EG algorithm. We formally state the results of OGDA in Section 6 and postpone the detailed analysis of OGDA in Section E.

Sum-of-Squares (SOS) Polynomials. Let $x$ be a set of variables. We denote the set of real polynomials in $x$ as $\mathbb{R}[x]$. We say that polynomial $p(x) \in \mathbb{R}[x]$ is an SOS polynomial if there exist polynomials $\left\{q_{i}(\boldsymbol{x}) \in \mathbb{R}[\boldsymbol{x}]\right\}_{i \in[M]}$ such that $p(\boldsymbol{x})=\sum_{i \in[M]} q_{i}(\boldsymbol{x})^{2}$. We denote the set of SOS polynomials in $x$ as $\operatorname{SOS}[x]$. Note that any SOS polynomial is non-negative.

SOS Programs. In Figure 1 we present a generic formulation of a degree- $d$ SOS program. The SOS program takes three kinds of input, a polynomial $g(\boldsymbol{x})$, sets of polynomials $\left\{g_{i}(\boldsymbol{x})\right\}_{i \in[M]}$ and $\left\{h_{i}(\boldsymbol{x})\right\}_{i \in[N]}$. Each polynomial in $\{g(\boldsymbol{x})\} \cup\left\{g_{i}(\boldsymbol{x})\right\}_{i \in[M]} \cup\left\{h_{i}(\boldsymbol{x})\right\}_{i \in[N]}$ has degree of at most $d$. The SOS program searches for an SOS polynomial in the set of polynomials $\Sigma=\left\{g(x)+\sum_{i \in[M]} p_{i}(x)\right.$. $\left.g_{i}(\boldsymbol{x})+\sum_{i \in[N]} q_{i}(\boldsymbol{x}) \cdot h_{i}(\boldsymbol{x})\right\}$, where $\left\{p_{i}(\boldsymbol{x})\right\}_{i \in[M]}$ and $\left\{q_{i}(\boldsymbol{x})\right\}_{i \in[N]}$ are polynomials in $\boldsymbol{x}$. More precisely for each $i \in[M], p_{i}(\boldsymbol{x})$ is an SOS polynomial with degree at most $d-\operatorname{deg}\left(g_{i}(\boldsymbol{x})\right)$. For each $i \in[N], q_{i}(\boldsymbol{x})$ is a (not necessarily SOS) polynomial with degree at most $d-\operatorname{deg}\left(g_{i}(\boldsymbol{x})\right)$. Note that any polynomial in set $\Sigma$ is at most degree $d$. In our applications, we choose $\left\{g_{i}(\boldsymbol{x})\right\}_{i \in[M]}$ to be non-positive polynomials and $\left\{h_{i}(\boldsymbol{x})\right\}_{i \in[N]}$ to be polynomials that are equal to 0 . Any feasible solution to the program certifies the non-negativity of $g(x)$.

Roadmap of the Paper. In Section 3, we introduce our new performance measure - the tangent residual and prove some of its properties. In Section 4, we show that the EG algorithm enjoys bestiterate convergence. In Section 5, we strengthen the convergence guarantee for the EG algorithm and obtain the tight last-iterate convergence rate by showing that the tangent residual (Definition 3) is non-increasing across the iterations of the EG algorithm. The last-iterate convergence rate for the tangent residual also implies a last-iterate convergence rate for the gap function (Definition 1) and the natural residual (definition 4) as shown in Lemma 2 and Lemma 1. In Section 6,

## Input Fixed Polynomials.

- Polynomial $g(x)$
- Polynomial $g_{i}(\boldsymbol{x}) \in \mathbb{R}[\boldsymbol{x}]$ for all $i \in[M]$.
- Polynomial $h_{i}(\boldsymbol{x}) \in \mathbb{R}[\boldsymbol{x}]$ for all $i \in[N]$.


## Decision Variables of the SOS Program:

- $p_{i}(\boldsymbol{x}) \in \operatorname{SOS}[\boldsymbol{x}]$ is an SOS polynomial with degree at most $d-\operatorname{deg}\left(g_{i}\right)$, for all $i \in[M]$.
- $q_{i}(\boldsymbol{x}) \in \mathbb{R}[\boldsymbol{x}]$ is a polynomial with degree at $\operatorname{most} d-\operatorname{deg}\left(h_{i}\right)$, for all $i \in[N]$.


## Constraints of the SOS Program:

$$
g(x)+\sum_{i \in[M]} p_{i}(x) \cdot g_{i}(x)+\sum_{i \in[N]} q_{i}(x) \cdot h_{i}(x) \in \operatorname{SOS}[x]
$$

Figure 1: Generic degree $d$ SOS program.
we further prove the tight last-iterate convergence rate for the OGDA algorithm. The analysis of the OGDA algorithm follows the same steps as in the analysis of the EG algorithm, and we postpone most of the details in Appendix E.

## 3 The Tangent Residual and Its Properties

We formally introduce our performance measure the tangent residual . As discussed in Section 1.1, many standard and natural performance measures, i.e., the natural residual, $\left\|z_{k}-z_{k+1 / 2}\right\|^{9}$, $\left\|z_{k}-z_{k+1}\right\|, \max _{z \in \mathcal{Z}}\left\langle F(z), z_{k}-z\right\rangle$ and $\max _{z \in \mathcal{Z}}\left\langle F\left(z_{k}\right), z_{k}-z\right\rangle$, are unfortunately non-decreasing for EG. See Appendix $D$ for numerical examples.

Definition 2 (Unit Normal Cone). Given a closed convex set $\mathcal{Z} \subseteq \mathbb{R}^{n}$ and a point $z \in \mathcal{Z}$, we denote by $N_{\mathcal{Z}}(z)=\left\langle v \in \mathbb{R}^{n}:\left\langle v, z^{\prime}-z\right\rangle \leq 0, \forall z^{\prime} \in \mathcal{Z}\right\rangle$ the normal cone of $\mathcal{Z}$ at point $z$ and by $\widehat{N}_{\mathcal{Z}}(z)=\{v \in$ $\left.N_{\mathcal{Z}}(z):\|v\| \leq 1\right\}$ the intersection of the unit ball with the the normal cone of $\mathcal{Z}$ at $z$. Note that $\widehat{N}_{\mathcal{Z}}(z)$ is nonempty and compact for any $z \in \mathcal{Z}$, as $(0, \ldots, 0) \in \widehat{N}_{\mathcal{Z}}(z)$.

Definition 3 (Tangent Residual). Given an operator $F: \mathcal{Z} \rightarrow \mathbb{R}^{n}$ and a closed convex set $\mathcal{Z}$, let $T_{\mathcal{Z}}(z):=\left\{z^{\prime} \in \mathbb{R}^{n}:\left\langle z^{\prime}, a\right\rangle \leq 0, \forall a \in \mathcal{C}_{\mathcal{Z}}(z)\right\}$ be the tangent cone of $z$, and define $J_{\mathcal{Z}}(z):=\{z\}+T_{\mathcal{Z}}(z)$. The tangent residual of $F$ at $z \in \mathcal{Z}$ is defined as $r_{(F, \mathcal{Z})}^{\tan }(z):=\left\|\Pi_{J_{\mathcal{Z}}(z)}[z-F(z)]-z\right\|$. An equivalent definition is $r_{(F, \mathcal{Z})}^{\tan }(z):=\sqrt{\|F(z)\|^{2}-\max _{\substack{a \in \widehat{N}_{\mathcal{Z}}(z),\langle F(z), a\rangle \leq 0}}\langle a, F(z)\rangle^{2}}$.

Remark 2. We show the equivalence of the two definitions of tangent residual in Lemma 7. For the rest of the paper, we may use either of the two equivalent definitions depending on which one is more convenient.

[^7]When the convex set $\mathcal{Z}$ and the operator $F$ are clear from context, we are going to omit the subscript and denote the unit normal cone as $\widehat{N}(z)=\widehat{N}_{\mathcal{Z}}(z)$ and the tangent residual as $r^{\text {tan }}(z)=$ $r_{(F, \mathcal{Z})}^{\tan }(z)$. Although the definition is slightly technical, one can think of the tangent residual as the norm of another operator $\widehat{F}$, which is $F$ projected to all directions that are not "blocked" by the boundary of $\mathcal{Z}$ if one takes an infinitesimally small step $\epsilon \cdot F(z)$, which is the same as projecting $F$ to $J_{\mathcal{Z}}(z)$. Intuitively, if the tangent residual is small, then the next iterate will not be far away from the current one.

Next, we formally define the natural residual associated with the instance formally stated in Definition 4, and show how it is related to the tangent residual.

Definition 4. Consider an instance $\mathcal{I}$ of the variational inequality problem on convex set $\mathcal{Z} \subseteq \mathbb{R}^{n}$ and monotone operator $F: \mathcal{Z} \rightarrow \mathbb{R}^{n}$. For $z \in \mathcal{Z}$, the natural map and natural residual associated with $\mathcal{I}$ is defined as follows

$$
F_{K}^{n a t}(z)=z-\Pi_{\mathcal{Z}}(z-F(z)), \quad r_{(F, \mathcal{Z})}^{\text {nat }}(z)=\left\|F_{K}^{n a t}(z)\right\| .
$$

Given an instance of the monotone VI constrained on convex set $\mathcal{Z} \subseteq \mathbb{R}^{n}$ and operator $F$ : $\mathcal{Z} \rightarrow \mathbb{R}^{n}$, point $z^{*}$ is a solution of the monotone VI iff $r_{(F, \mathcal{Z})}^{n a t}\left(z^{*}\right)=0$. In Lemma 1 , we show that the tangent residual upper bounds the the natural residual. See Figure 2 for illustration of how the tangent residual relates to the natural residual.

Lemma 1. Consider an instance $\mathcal{I}$ of the variational inequality problem on convex set $\mathcal{Z} \subseteq \mathbb{R}^{n}$ and monotone operator $F: \mathcal{Z} \rightarrow \mathbb{R}^{n}$. For any $z \in \mathcal{Z}, r_{(F, \mathcal{Z})}^{\text {tan }} \geq r_{(F, \mathcal{Z})}^{\text {nat }}(z)$.
Proof. Let $w=\Pi_{\mathcal{Z}}(z-F(z))$ and $a_{1}=z-F(z)-w$. Observe that

$$
\|F(z)\|^{2}=\|z-w\|^{2}+\left\|a_{1}\right\|^{2}-2\left\langle z-w, a_{1}\right\rangle
$$

Since $r_{(F, \mathcal{Z})}^{n a t}(z)^{2}=\|z-w\|^{2}$ and $\left\langle z-w, a_{1}\right\rangle \leq 0$, we have $r_{(F, \mathcal{Z})}^{n a t}(z)^{2} \leq\|F(z)\|^{2}-\left\|a_{1}\right\|^{2}$.
According to Lemma $7, r^{\text {tan }}(z)^{2}=\left\|\Pi_{J_{\mathcal{Z}}(z)}[z-F(z)]-z\right\|^{2}$, where $J_{\mathcal{Z}}(z):=z+T_{\mathcal{Z}}(z)$ and $T_{\mathcal{Z}}(z)=\left\{z^{\prime} \in \mathbb{R}^{n}:\left\langle z^{\prime}, a\right\rangle \leq 0, \forall a \in \mathcal{C}_{\mathcal{Z}}(z)\right\}$ is the tangent cone of $z$. Since $J_{\mathcal{Z}}(z)$ is a cone with origin $z$, we have $\left\langle z-F(z)-\Pi_{J \mathcal{Z}(z)}[z-F(z)], z-\Pi_{J_{\mathcal{Z}}(z)}[z-F(z)]\right\rangle=0$, and $\left\|\Pi_{J \mathcal{Z}(z)}[z-F(z)]-z\right\|^{2}=\|F(z)\|^{2}-\left\|z-F(z)-\Pi_{J \mathcal{Z}(z)}[z-F(z)]\right\|^{2}$. As $\mathcal{Z} \subseteq J_{\mathcal{Z}}(z),\left\|a_{1}\right\|^{2} \geq$ $\left\|z-F(z)-\Pi_{J_{z}(z)}[z-F(z)]\right\|^{2}$, which implies that

$$
r_{(F, \mathcal{Z})}^{\text {nat }}(z)^{2} \leq\left\|\Pi_{J \mathcal{Z}(z)}[z-F(z)]-z\right\|^{2}=r^{\tan }(z)^{2}
$$

Due to the above lemma, an upper bound of the tangent residual is also an upper bound of the natural residual. We show in Theorem 2 the monotonicity of the tangent residual of the EG updates, which is the technical core of our analysis and implies the $O\left(\frac{1}{\sqrt{T}}\right)$ convergence rate of the


Figure 2: Illustration of the tangent residual and the natural residual. The blue line represents the tangent residual and the red line represents the natural residual. It is clear that the tangent residual upper bounds the natural residual.
tangent residual. As a result, we also show that the natural residual has a $O\left(\frac{1}{\sqrt{T}}\right)$ convergence rate. One may be tempted to directly use the natural residual as the convergence measure. However, from our numerical experiments, the natural residual of the EG updates is not monotone, and we believe that it is very challenging to directly establish the convergence rate for the natural residue without using the tangent residual as a proxy.

In the next lemma, we argue why a small tangent residual implies a small gap function, hence an approximate solution of the variational inequality. The proof is postponed to Appendix A.

Lemma 2. [Adapted from the proof of Theorem 10 in [Golowich et al., 2020b].] Given a closed convex set $\mathcal{Z} \in \mathbb{R}^{n}$, an operator $F: \mathcal{Z} \rightarrow \mathbb{R}^{n}$ and $z \in \mathcal{Z}$, we have

$$
\operatorname{GAP}_{\mathcal{Z}, F, D}(z):=\max _{z^{\prime} \in \mathcal{Z} \cap \mathcal{B}(z, D)}\left\langle F(z), z-z^{\prime}\right\rangle \leq D \cdot r_{(F, \mathcal{Z})}^{\tan }(z) .
$$

If we have a convex-concave function $f(z): \mathcal{Z} \rightarrow \mathbb{R}$ such that $z=(x, y), \mathcal{Z}=\mathcal{X} \times \mathcal{Y}$ where $\mathcal{X}$ and $\mathcal{Y}$ are closed convex sets, let $F(x, y)=\binom{\nabla_{x} f(x, y)}{-\nabla_{y} f(x, y)}$, then the duality gap at $z$ with respect to $\mathcal{X}^{\prime}$ and $\mathcal{Y}^{\prime}$ is $\mathrm{dg}_{f}^{\mathcal{X}^{\prime}, \mathcal{Y}^{\prime}}(z):=\max _{y^{\prime} \in \mathcal{Y}^{\prime}} f\left(x, y^{\prime}\right)-\min _{x^{\prime} \in \mathcal{X}^{\prime}} f\left(x^{\prime}, y\right) \leq D \sqrt{2} \cdot r_{(F, \mathcal{Z})}^{\text {tan }}(z)$, if $z \in \mathcal{X}^{\prime} \times \mathcal{Y}^{\prime}$ and the diameters of $\mathcal{X}^{\prime}$ and $\mathcal{Y}^{\prime}$ are both upper bounded by $D .{ }^{10}$

## 4 Best-Iterate Convergence of EG with Constant Step Size

En route to establish the last-iterate convergence of the EG algorithm, we first show a weaker guarantee known as the best-iterate convergence. Lemma 3 implies that after running EG for $T$ steps, there exists an iteration $t^{*} \in[T]$ where $\left\|z_{t^{*}}-z_{t^{*}+\frac{1}{2}}\right\|^{2} \leq O\left(\frac{1}{T}\right)$. The proof can be found in [Korpelevich, 1976] and [Facchinei and Pang, 2007] (included in Appendix B for completeness).

[^8]Lemma 3 ([Korpelevich, 1976, Facchinei and Pang, 2007]). Let $\mathcal{Z}$ be a closed convex set in $\mathbb{R}^{n}, F(\cdot)$ be a monotone and L-Lipschitz operator mapping from $\mathcal{Z}$ to $\mathbb{R}^{n}$. For any solution $z^{*}$ of the monotone VI, that is, $\left\langle F\left(z^{*}\right), z^{*}-z\right\rangle \leq 0$ for all $z \in \mathcal{Z}$. For all $k$,

$$
\begin{equation*}
\left\|z_{k}-z^{*}\right\|^{2} \geq\left\|z_{k+1}-z^{*}\right\|^{2}+\left(1-\eta^{2} L^{2}\right)\left\|z_{k}-z_{k+\frac{1}{2}}\right\|^{2} . \tag{8}
\end{equation*}
$$

In Lemma 4, we relate $\left\|z_{k}-z_{k+\frac{1}{2}}\right\|$ with the tangent residual at $z_{k+1}$, and derive the best-iterate convergence guarantee in terms of the tangent residual in Lemma 5. The proofs of Lemma 4 and 5 are postponed to Appendix B.
Lemma 4. For all $k, r^{\text {tan }}\left(z_{k+1}\right) \leq\left(1+\eta L+(\eta L)^{2}\right) \frac{\left\|z_{k}-z_{k+1 / 2}\right\|}{\eta}$.
In lemma 5, we argue the tangent residual has a best-iterate convergence with rate $O\left(\frac{1}{\sqrt{T}}\right)$.
Lemma 5. Let $\mathcal{Z}$ be a closed convex set in $\mathbb{R}^{n}, F(\cdot)$ be a monotone and L-Lipschitz operator mapping from $\mathcal{Z}$ to $\mathbb{R}^{n}$. Suppose the step size of the EG algorithm $\eta \in\left(0, \frac{1}{L}\right)$, then for any solution $z^{*}$ of the monotone VI and any integer $T>0$, there exists $t^{*} \in[T]$ such that:

$$
\left\|z_{t^{*}}-z_{t^{*}+\frac{1}{2}}\right\|^{2} \leq \frac{1}{T} \frac{\left\|z_{0}-z^{*}\right\|^{2}}{1-(\eta L)^{2}}, \quad \text { AND } \quad r^{\tan }\left(z_{t^{*}+1}\right) \leq \frac{1+\eta L+(\eta L)^{2}}{\eta} \frac{1}{\sqrt{T}} \frac{\left\|z_{0}-z^{*}\right\|}{\sqrt{1-(\eta L)^{2}}}
$$

## 5 Last-Iterate Convergence of EG with Constant Step Size

In this section, we show that the last-iterate convergence rate is $O\left(\frac{1}{\sqrt{T}}\right)$. In particular, we prove that the tangent residual is non-increasing, which, in combination with Lemma 5 , implies the lastiterate convergence rate of EG. To establish the monotonicity of the tangent residual, we combine SOS programming with the low-dimensionality of the EG update rule. To better illustrate our approach, we first prove the result in the unconstrained setting (Section 5.1), then show how to generalize it to the constrained setting (Section 5.2).

### 5.1 Warm Up: Unconstrained Case

As a warm-up, we consider the unconstrained setting where $\mathcal{Z}=\mathbb{R}^{n}$. Although the last-iterate convergence rate is known in the unconstrained setting due to [Golowich et al., 2020b, Gorbunov et al., 2021], we provide a simpler proof that also permits a larger step size. Our analysis holds for any step size $\eta \in\left(0, \frac{1}{L}\right)$, while the previous analysis requires $\eta \leq \frac{1}{\sqrt{2} L}$ [Gorbunov et al., 2021].

Let $z_{k}$ be the $k$-th iterate of the EG method. In Theorem 1, we show that the tangent residual is monotone in the unconstrained setting. ${ }^{11}$ Our approach is to apply SOS programming to search for a certificate of non-negativity for $\left\|F\left(z_{k}\right)\right\|^{2}-\left\|F\left(z_{k+1}\right)\right\|^{2}$ for every $k$, over the semialgebraic set

[^9]defined by the following polynomial constraints in variables $\left\{z_{i}[\ell], \eta F\left(z_{i}\right)[\ell]\right\}_{i \in\left\{k, k+\frac{1}{2}, k+1\right\}, \ell \in[n]}$ :
\[

$$
\begin{aligned}
& z_{k+\frac{1}{2}}[\ell]-z_{k}[\ell]+\eta F\left(z_{k}\right)[\ell]=0, \quad z_{k+1}[\ell]-z_{k}[\ell]+\eta F\left(z_{k+\frac{1}{2}}[\ell]=0, \quad \forall \ell \in[n], \quad\right. \text { (EG Update) } \\
& \left\|\eta F\left(z_{i}\right)-\eta F\left(z_{j}\right)\right\|^{2}-(\eta L)^{2}\left\|z_{i}-z_{j}\right\|^{2} \leq 0, \quad \forall i, j \in\left\{k, k+\frac{1}{2}, k+1\right\}, \quad \text { (Lipschitzness) } \\
& \left\langle\eta F\left(z_{i}\right)-\eta F\left(z_{j}\right), z_{j}-z_{i}\right\rangle \leq 0, \quad \forall i, j \in\left\{k, k+\frac{1}{2}, k+1\right\} . \quad \text { (Monotonicity) }
\end{aligned}
$$
\]

We always multiply $F$ with $\eta$ in the constraints as it will be convenient later. We use $K$ to denote the set $\left\{k, k+\frac{1}{2}, k+1\right\}$. To obtain a certificate of non-negativity, we apply SOS programming to search for a degree-2 SOS proof. More specifically, we want to find non-negative coefficients $\left\{\lambda_{i, j}^{*}, \mu_{i, j}^{*}\right\}_{i>j, i, j \in K}$ and degree-1 polynomials $\gamma_{1}^{(\ell)}(\boldsymbol{w})$ and $\gamma_{2}^{(\ell)}(\boldsymbol{w})$ in $\mathbb{R}[\boldsymbol{w}]$ for each $\ell \in[n]$, where $\boldsymbol{w}:=\left\{z_{i}[\ell], \eta F\left(z_{i}\right)[\ell]\right\}_{i \in K, \ell \in[n]}$, such that the following is an SOS polynomial:

$$
\begin{align*}
& \left\|\eta F\left(z_{k}\right)\right\|^{2}-\left\|\eta F\left(z_{k+1}\right)\right\|^{2}+\sum_{i>j \text { and } i, j \in K} \lambda_{i, j}^{*} \cdot\left(\left\|\eta F\left(z_{i}\right)-\eta F\left(z_{j}\right)\right\|^{2}-(\eta L)^{2}\left\|z_{i}-z_{j}\right\|^{2}\right) \\
& \left.+\sum_{i>j \text { and } i, j \in K} \mu_{i, j}^{*} \cdot\left\langle\eta F\left(z_{i}\right)-\eta F\left(z_{j}\right)\right), z_{j}-z_{i}\right\rangle+\sum_{\ell \in[n]} \gamma_{1}^{(\ell)}(\boldsymbol{w})\left(z_{k+\frac{1}{2}}[\ell]-z_{k}[\ell]+\eta F\left(z_{k}\right)[\ell]\right) \\
& +\sum_{\ell \in[n]} \gamma_{2}^{(\ell)}(\boldsymbol{w})\left(z_{k+1}[\ell]-z_{k}[\ell]+\eta F\left(z_{k+\frac{1}{2}}\right)[\ell]\right) . \tag{9}
\end{align*}
$$

Due to constraints satisfied by the EG iterates, the non-negativity of Expression (9) clearly implies that $\left\|F\left(z_{k}\right)\right\|^{2}-\left\|F\left(z_{k+1}\right)\right\|^{2}$ is non-negative. However, Expression (9) is in fact an infinite family of polynomials rather than a single one. Expression (9) corresponds to a different polynomial for every integer $n$. To directly search for the solution, we would need to solve an infinitely large SOS program, which is clearly infeasible. By exploring the symmetry in Expression (9), we show that it suffices to solve a constant size SOS program. Let us first expand Expression (9) as follows:

$$
\begin{align*}
& \sum_{\ell \in[n]}\left(\left(\eta F\left(z_{k}\right)[\ell]\right)^{2}-\left(\eta F\left(z_{k+1}\right)[\ell]\right)^{2}+\sum_{i>j \text { and } i, j \in K} \lambda_{i, j}^{*}\left(\left(\eta F\left(z_{i}\right)[\ell]-\eta F\left(z_{j}\right)[\ell]\right)^{2}-(\eta L)^{2}\left(z_{i}[\ell]-z_{j}[\ell]\right)^{2}\right)\right. \\
&\left.\quad+\sum_{i>j \text { and } i, j \in K} \mu_{i, j}^{*}\left(\eta F\left(z_{i}\right)[\ell]-\eta F\left(z_{j}\right)[\ell]\right)\right)\left(z_{j}[\ell]-z_{i}[\ell]\right)+\gamma_{1}^{(\ell)}(\boldsymbol{w})\left(z_{k+\frac{1}{2}}[\ell]-z_{k}[\ell]+\eta F\left(z_{k}\right)[\ell]\right) \\
&\left.+\gamma_{2}^{(\ell)}(\boldsymbol{w})\left(z_{k+1}[\ell]-z_{k}[\ell]+\eta F\left(z_{k+\frac{1}{2}}\right)[\ell]\right)\right) . \tag{10}
\end{align*}
$$

What we will argue next is that, due to the symmetry across coordinates, it suffices to directly search for a single SOS proof that shows that each of the $n$ summands in Expression (10) is an SOS polynomial. More specifically, we make use of the following two key properties. (i) For any $\ell, \ell^{\prime} \in[n]$, the $\ell$-th summand and $\ell^{\prime}$-th summand are identical subject to a change of variable, ${ }^{12}$ (ii)

[^10]the $\ell$-th summand only depends on the coordinate $\ell$, i.e., variables in $\left\{z_{i}[\ell], \eta F\left(z_{i}\right)[\ell]\right\}_{i \in K}$ and does not involve any other coordinates. ${ }^{13}$ We solve the following SOS program, whose solution can be used to construct $\left\{\lambda_{i, j}^{*}, \mu_{i, j}^{*}\right\}_{i>j, i, j \in K}$ and $\left\{\gamma_{1}^{(\ell)}(\boldsymbol{w}), \gamma_{2}^{(\ell)}(\boldsymbol{w})\right\}_{\ell \in[n]}$ so that each of the summands in Expression (10) is an SOS polynomial.

Input Fixed Polynomials. We use $x$ to denote $\left(x_{0}, x_{1}, x_{2}\right)$ and $y$ to denote $\left(y_{0}, y_{1}, y_{2}\right)$. Interpret $x_{i}$ as $z_{k+\frac{i}{2}}[\ell]$ and $y_{i}$ as $\eta F\left(z_{k+\frac{i}{2}}\right)[\ell]$ for $0 \leq i \leq 2$. Observe that $h_{1}(x, y)$ and $h_{2}(x, y)$ come from the EG update rule on coordinate $\ell . g_{i, j}^{L}(x, y)$ and $g_{i, j}^{m}(x, y)$ come from the $\ell$-th coordinate's contribution in the Lipschitzness and monotonicity constraints.

- $h_{1}(\boldsymbol{x}, \boldsymbol{y}):=x_{1}-x_{0}+y_{0}$ and $h_{2}(\boldsymbol{x}, \boldsymbol{y}):=x_{2}-x_{0}+y_{1}$.
- $g_{i, j}^{L}(\boldsymbol{x}, \boldsymbol{y}):=\left(y_{i}-y_{j}\right)^{2}-C \cdot\left(x_{i}-x_{j}\right)^{2}$ for any $0 \leq j<i \leq 2$. ${ }^{a}$
- $g_{i, j}^{m}(x, y):=\left(y_{i}-y_{j}\right)\left(x_{j}-x_{i}\right)$ for any $0 \leq j<i \leq 2$.


## Decision Variables of the SOS Program:

- $p_{i, j}^{L} \geq 0$, and $p_{i, j}^{m} \geq 0$, for all $0 \leq j<i \leq 2$.
- $q_{1}(\boldsymbol{x}, \boldsymbol{y})$ and $q_{2}(\boldsymbol{x}, \boldsymbol{y})$ are two degree 1 polynomials in $\mathbb{R}[\boldsymbol{x}, \boldsymbol{y}]$.


## Constraints of the SOS Program:

$$
\begin{align*}
\text { s.t. } \quad y_{0}^{2}-y_{2}^{2}+\sum_{2 \geq i>j \geq 0} p_{i, j}^{L} \cdot g_{i, j}^{L}(x, y) & +\sum_{2 \geq i>j \geq 0} p_{i, j}^{m} \cdot g_{i, j}^{m}(x, y)  \tag{11}\\
& +q_{1}(x, y) \cdot h_{1}(x, y)+q_{2}(x, y) \cdot h_{2}(x, y) \in \operatorname{SOS}[x, y] .
\end{align*}
$$

[^11]Figure 3: Our SOS program in the unconstrained setting.
The proof of the following theorem is based on a feasible solution to the SOS program in Figure 3.

Theorem 1. Let $F: \mathbb{R}^{n} \rightarrow \mathbb{R}^{n}$ be a monotone and L-Lipschitz operator. Then for any $k \in \mathbb{N}$, the $E G$ algorithm with step size $\eta \in\left(0, \frac{1}{L}\right)$ satisfies $\left\|F\left(z_{k}\right)\right\|^{2} \geq\left\|F\left(z_{k+1}\right)\right\|^{2}$.

Proof. Since $F$ is monotone and $L$-Lipschitz, we have

$$
\left\langle F\left(z_{k+1}\right)-F\left(z_{k}\right), z_{k}-z_{k+1}\right\rangle \leq 0
$$

and

$$
\left\|F\left(z_{k+\frac{1}{2}}\right)-F\left(z_{k+1}\right)\right\|^{2}-L^{2}\left\|z_{k+\frac{1}{2}}-z_{k+1}\right\|^{2} \leq 0 .
$$

[^12]We simplify them using the update rule of EG and $\eta L<1$. In particular, we replace $z_{k}-z_{k+1}$ with $\eta F\left(z_{k+\frac{1}{2}}\right)$ and $z_{k+\frac{1}{2}}-z_{k+1}$ with $\eta F\left(z_{k+\frac{1}{2}}\right)-\eta F\left(z_{k}\right)$.

$$
\begin{align*}
& \left\langle F\left(z_{k+1}\right)-F\left(z_{k}\right), F\left(z_{k+\frac{1}{2}}\right)\right\rangle \leq 0  \tag{12}\\
& \left\|F\left(z_{k+\frac{1}{2}}\right)-F\left(z_{k+1}\right)\right\|^{2}-\left\|F\left(z_{k+\frac{1}{2}}\right)-F\left(z_{k}\right)\right\|^{2} \leq 0 \tag{13}
\end{align*}
$$

In Proposition 1 at Appendix $C$ we verify the following identity.

$$
\left\|F\left(z_{k}\right)\right\|^{2}-\left\|F\left(z_{k+1}\right)\right\|^{2}+2 \cdot \text { LHS of Inequality }(12)+\text { LHS of Inequality }(13)=0
$$

Thus, $\left\|F\left(z_{k}\right)\right\|^{2}-\left\|F\left(z_{k+1}\right)\right\|^{2} \geq 0$.
Corollary 1 is implied by combing Lemma 2, Lemma 5, Theorem 1 and the fact that $\eta \in\left(0, \frac{1}{L}\right)$.
Corollary 1. Let $F(\cdot): \mathbb{R}^{n} \rightarrow \mathbb{R}^{n}$ be a monotone and L-Lipshitz operator and $z^{*} \in \mathbb{R}^{n}$ be a solution to the variational inequality. For any $T \geq 1$, let $z_{T}$ be $T$-th iterate of the $E G$ algorithm with constant step size $\eta \in\left(0, \frac{1}{L}\right)$, then $\operatorname{GAP}_{\mathbb{R}^{n}, F, D}\left(z_{T}\right) \leq \frac{1}{\sqrt{T}} \frac{3 D\left\|z_{0}-z^{*}\right\|}{\eta \sqrt{1-(\eta L)^{2}}}$.

### 5.2 Last-Iterate Convergence of EG with Arbitrary Convex Constraints

We establish the last-iterate convergence rate of the EG algorithm in the constrained setting in this section. The plan is similar to the one in Section 5.1. First, we use the assistance of SOS programming to prove the monotonicity of the tangent residual (Theorem 2), then combine it with the best-iterate convergence guarantee from Lemma 5 to derive the last-iterate convergence rate (Theorem 3).

Due to the constraints, proving the monotonicity of the tangent residual becomes much more challenging. The tangent residual in the constrained setting (Definition 3) is significantly more complex than its counterpart in the unconstrained setting. In Lemma 6, we introduce an auxiliary point $c(z)$ for every point $z$ that can be used to simplified the tangent residual.
Lemma 6. Let $\mathcal{Z} \subseteq \mathbb{R}^{n}$ be a closed convex set and $F: \mathcal{Z} \rightarrow \mathbb{R}$ be an operator. For any $z \in \mathcal{Z}$, denote $c(z):=\Pi_{N(z)}[-F(z)]$ the projection of $-F(z)$ on the normal cone $N(z)$. Then we have

- $r^{\text {tan }}(z)=\|F(z)+c(z)\|$,
- $\langle F(z)+c(z), c(z)\rangle=0$,
- $\langle F(z)+c(z), a\rangle \geq 0, \forall a \in N(z)$.

Proof. According to the definition of $c(z), r^{\tan }(z)=\|F(z)+c(z)\|$ follows from Lemma 7. Since $c(z)=\Pi_{N(z)}[-F(z)]$, we know that for all $a \in N(z)$,

$$
\begin{equation*}
\langle-F(z)-c(z), a-c(z)\rangle \leq 0 . \tag{14}
\end{equation*}
$$

Note that $c(z) \in N(z)$ and $N(z)$ is a cone. By substituting $a=0$ and $a=2 \cdot c(z)$ in (14), we get

$$
\langle-F(z)-c(z), c(z)\rangle=0 .
$$

Therefore, for all $a \in N(z)$, we have

$$
\langle-F(z)-c(z), a\rangle=\langle-F(z)-c(z), a-c(z)\rangle \leq 0 .
$$

Next, we need to decide over which semialgebraic set that we want to certify the nonnegativity of $r^{\text {tan }}\left(z_{k}\right)^{2}-r^{\text {tan }}\left(z_{k+1}\right)^{2}$. Naturally, we would like to use all constraints of $\mathcal{Z}$, but there might be arbitrarily many of them. In the next paragraph, we argue how to reduce the number of constraints.

Reducing the Number of Constraints. Suppose we are not given the description of $\mathcal{Z} \subseteq \mathbb{R}^{n}$, and we only observe one iteration of the EG algorithm. In other words, we know $z_{k}, z_{k+\frac{1}{2}}$, and $z_{k+1}$, as well as $F\left(z_{k}\right), F\left(z_{k+\frac{1}{2}}\right)$, and $F\left(z_{k+1}\right)$. To express the squared tangent residual at $z_{k}$ and the squared tangent residual at $z_{k+1}$, let us also assume that the vector $c_{k}=\Pi_{N\left(z_{k}\right)}\left[-F\left(z_{k}\right)\right]$ and $c_{k+1}=\Pi_{N\left(z_{k+1}\right)}\left[-F\left(z_{k+1}\right)\right]$, and according to Lemma 6, we have $r^{\tan }\left(z_{k}\right)^{2}=\left\|F\left(z_{k}\right)+c_{k}\right\|^{2}$, and $r^{\tan }\left(z_{k+1}\right)^{2}=\left\|F\left(z_{k+1}\right)+c_{k+1}\right\|^{2}$. Our plan is to derive a set of inequalities that must be satisfied by these vectors. From this limited information, what can we learn about $\mathcal{Z}$ ? We can conclude that $\mathcal{Z}$ must lie in the intersection of the following halfspaces: (a) $\left\langle c_{k}, z\right\rangle \leq\left\langle c_{k}, z_{k}\right\rangle$. This is true because $c_{k} \in N\left(z_{k}\right)$. (b) $\left\langle a_{k+\frac{1}{2}}, z\right\rangle \geq\left\langle a_{k+\frac{1}{2}}, z_{k+\frac{1}{2}}\right\rangle$, where $a_{k+\frac{1}{2}}=-\left(z_{k}-\eta F\left(z_{k}\right)-z_{k+\frac{1}{2}}\right)$. This is true because $z_{k+\frac{1}{2}}=\Pi_{\mathcal{Z}}\left(z_{k}-\eta F\left(z_{k}\right)\right)$, so $-a_{k+\frac{1}{2}} \in N\left(z_{k+\frac{1}{2}}\right)$. (c) $\left\langle a_{k+1}, z\right\rangle \geq\left\langle a_{k+1}, z_{k+1}\right\rangle$, where $a_{k+1}=$ $-\left(z_{k}-\eta F\left(z_{k+\frac{1}{2}}\right)-z_{k+1}\right)$. This is true because $z_{k+1} \stackrel{=}{=} \Pi_{\mathcal{Z}}\left(z_{k}-\eta F\left(z_{k+\frac{1}{2}}\right)\right)$, so $-a_{k+1} \in N\left(z_{k+1}\right)$. See Figure 4 for illustration. Additionally, due to our definition of $c_{k}$ and $c_{k+1}$ and Lemma 6, we know that (d) $\left\langle\eta F\left(z_{i}\right)+\eta c_{i}, \eta c_{i}\right\rangle=0$ for $i \in\{k, k+1\}$, and (e) $\left\langle\eta F\left(z_{k+1}\right)+\eta c_{k+1}, a_{k+1}\right\rangle \leq 0$ as $-a_{k+1} \in N\left(z_{k+1}\right)$.

Clearly, for any $\mathcal{Z}$, the inequalities in (a) to (e) must hold, though there might be other inequalities that are also true. Our goal is to prove that the tangent residual is non-increasing even if only inequalities (a) to (e) hold. If we can do so, then we prove that tangent residual is non-increasing for an arbitrary $\mathcal{Z}$.

Formulation as SOS program. Similar to the unconstrained case, our plan is to search for a certificate of non-negativity of the following expression

$$
\begin{equation*}
\left\|F\left(z_{k}\right)+c_{k}\right\|^{2}-\left\|F\left(z_{k+1}\right)+c_{k+1}\right\|^{2} \tag{15}
\end{equation*}
$$



Figure 4: Reducing the number of constraints.
over the semialgebraic set defined by the following polynomial constraints in variables $\left\{\left\{z_{i}[\ell], \eta F\left(z_{i}\right)[\ell]\right\}_{i \in\left\{k, k+\frac{1}{2}, k+1\right\}} \cup\left\{c_{i}[\ell]\right\}_{i \in k, k+1}\right\}_{\ell \in[n]}$
$\left\|\eta F\left(z_{i}\right)-\eta F\left(z_{j}\right)\right\|^{2}-(\eta L)^{2}\left\|z_{i}-z_{j}\right\|^{2} \leq 0, \quad \forall i, j \in\left\{k, k+\frac{1}{2}, k+1\right\}, \quad$ (Lipschitzness)
$\left\langle\eta F\left(z_{i}\right)-\eta F\left(z_{j}\right), z_{j}-z_{i}\right\rangle \leq 0, \quad \forall i, j \in\left\{k, k+\frac{1}{2}, k+1\right\}, \quad$ (Monotonicity)
$\left\langle a_{i}, z_{i}-z_{j}\right\rangle \leq 0$,
$\left\langle\eta c_{i}, z_{j}-z_{i}\right\rangle \leq 0$,
$\forall i \in\left\{k+\frac{1}{2}, k+1\right\}, j \in\left\{k, k+\frac{1}{2}, k+1\right\}, \quad\left(-a_{i} \in N\left(z_{i}\right)\right)$ $\forall i \in\{k, k+1\}, j \in\left\{k, k+\frac{1}{2}, k+1\right\}, \quad\left(c_{i} \in N\left(z_{i}\right)\right)$
$\left\langle\eta F\left(z_{i}\right)+\eta c_{i}, \eta c_{i}\right\rangle=0, \quad \forall i \in\{k, k+1\}, \quad$ (Lemma 6)
$\left\langle\eta F\left(z_{k+1}\right)+\eta c_{k+1}, a_{k+1}\right\rangle \leq 0$,
(Lemma 6).
Similar to Section 5, we multiply the operators, $c_{k}$, and $c_{k+1}$ with $\eta$ for convenience. Fortunately, the dimensional-dependent Expression (15) and semialgebraic set are symmetric across coordinates, and more specifically, satisfy the two key properties in the unconstrained case - Property (i) and (ii). Hence, we can represent all of the coordinates $\ell \geq 1$ with one coordinate in the SOS program, and we can form a constant size SOS program to search for a certificate of non-negativity for Expression (15) as shown in Figure 5.

In Theorem 2, we establish the monotonicity of the tangent residual. Our proof is based on the solution to the degree-2 SOS program concerning polynomials in 8 variables (Figure 5).

Theorem 2. Let $\mathcal{Z} \subseteq \mathbb{R}^{n}$ be a closed convex set and $F: \mathcal{Z} \rightarrow \mathbb{R}^{n}$ be a monotone and L-Lipschitz operator. For any step size $\eta \in\left(0, \frac{1}{L}\right)$ and any $z_{k} \in \mathcal{Z}$, the $E G$ method update satisfies $r_{(F, \mathcal{Z})}^{\text {tan }}\left(z_{k}\right) \geq r_{(F, \mathcal{Z})}^{\text {tan }}\left(z_{k+1}\right)$.

Input Fixed Polynomials. We use $\boldsymbol{x}$ to denote $\left(x_{0}, x_{1}, x_{2}\right), \boldsymbol{y}$ to denote $\left(y_{0}, y_{1}, y_{2}\right)$ and $\boldsymbol{w}$ to denote $\left(w_{0}, w_{2}\right)$. Interpret $x_{i}$ as $z_{k+\frac{i}{2}}[\ell]$ and $y_{i}$ as $\eta F\left(z_{k+\frac{i}{2}}\right)[\ell]$ for $0 \leq i \leq 2, w_{0}$ as $\eta c_{k}[\ell]$ and $w_{2}$ as $\eta c_{k+1}[\ell]$. Let $b_{1}=$ $-\left(x_{0}-y_{0}-x_{1}\right)$ and $b_{2}=-\left(x_{0}-y_{1}-x_{2}\right)$.
Origin of Constraints. $g_{i, j}^{L}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{w})$ and $g_{i, j}^{m}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{w})$ come from the $\ell$-th coordinate's contribution in the Lipschitzness and monotonicity constraints. Similarly, $g_{i, j}^{b}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{w})$ and $g_{i, j}^{w}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{w})$ come from the $\ell$-th coordinate contribution of fact that $-a_{i}$ and $c_{i}$ are in the normal cone of $z_{i}$. Finally, $h_{i}^{w}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{w})$ and $g^{r}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{w})$ comes from the $\ell$-th coordinate contribution due to the inequalities of Lemma 6.

- $g_{i, j}^{L}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{w}):=\left(y_{i}-y_{j}\right)^{2}-C \cdot\left(x_{i}-x_{j}\right)^{2}$ for any $0 \leq j<i \leq 2{ }^{a}$
- $g_{i, j}^{m}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{w}):=\left(y_{i}-y_{j}\right)\left(x_{j}-x_{i}\right)$ for any $0 \leq j<i \leq 2$.
- $g_{i, j}^{b}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{w}):=b_{i} \cdot\left(x_{i}-x_{j}\right)$ for any $i \in\{1,2\}, 0 \leq j \leq 2$.
- $g_{i, j}^{w}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{w}):=w_{i} \cdot\left(x_{j}-x_{i}\right)$ for any $i \in\{0,2\}, 0 \leq j \leq 2$.
- $g^{r}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{w}):=\left(y_{2}+w_{2}\right) \cdot b_{2}$.
- $h_{i}^{w}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{w}):=\left(y_{i}+w_{i}\right) \cdot w_{i}$ for any $i \in\{0,2\}$.


## Decision Variables of the SOS Program:

- $p_{i, j}^{L} \geq 0$, and $p_{i, j}^{m} \geq 0$, for all $0 \leq j<i \leq 2$.
- $p_{i, j}^{b} \geq 0$, for any $i \in\{1,2\}, 0 \leq j \leq 2$.
- $p_{i, j}^{w} \geq 0$, for any $i \in\{0,2\}, 0 \leq j \leq 2$.
- $p^{r} \geq 0$.
- $q_{0}^{w}, q_{2}^{w} \in \mathbb{R}$.


## Constraints of the SOS Program:

$$
\begin{aligned}
\text { s.t. } \quad \begin{aligned}
\left(y_{0}\right. & \left.+w_{0}\right)^{2}-\left(y_{2}+w_{2}\right)^{2}+\sum_{2 \geq i>j \geq 0} p_{i, j}^{L} \cdot g_{i, j}^{L}(x, y, \boldsymbol{w})+\sum_{2 \geq i>j \geq 0} p_{i, j}^{m} \cdot g_{i, j}^{m}(x, y, \boldsymbol{w}) \\
& +\sum_{i \in\{1,2\}, 2 \geq j \geq 0} p_{i, j}^{b} \cdot g_{i, j}^{b}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{w})+\sum_{i \in\{0,2\}, 2 \geq j \geq 0} p_{i, j}^{w} \cdot g_{i, j}^{w}(x, y, \boldsymbol{w}) \\
& +p^{r} \cdot g^{r}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{w})+\sum_{i \in\{0,2\}} q_{i}^{w} \cdot h_{i}^{w w}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{w})
\end{aligned} \in \operatorname{SOS}[\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{w}]
\end{aligned}
$$

[^13]Figure 5: Our SOS program in the constrained setting.

Proof. Let $c_{k}=\Pi_{N_{\mathcal{Z}}\left(z_{k}\right)}\left(-F\left(z_{k}\right)\right)$ and $c_{k+1}=\Pi_{N_{\mathcal{Z}}\left(z_{k+1}\right)}\left(-F\left(z_{k+1}\right)\right)$. By Lemma 6 we have

$$
\begin{equation*}
\eta^{2} r^{\tan }\left(z_{k}\right)^{2}-\eta^{2} r^{\tan }\left(z_{k+1}\right)^{2}=\left\|\eta F\left(z_{k}\right)+\eta c_{k}\right\|^{2}-\left\|\eta F\left(z_{k+1}\right)+\eta c_{k+1}\right\|^{2} \tag{17}
\end{equation*}
$$

Combining the monotonicity and $L$-Lipschitzness of $F$ with the fact that $L \leq \frac{1}{\eta}$, we have

$$
\begin{align*}
& (-1) \cdot\left(\left\|z_{k+\frac{1}{2}}-z_{k+1}\right\|^{2}-\left\|\eta F\left(z_{k+\frac{1}{2}}\right)-\eta F\left(z_{k+1}\right)\right\|^{2}\right) \leq 0,  \tag{18}\\
& \left.(-2) \cdot\left\langle\eta F\left(z_{k+1}\right)-\eta F\left(z_{k}\right), z_{k+1}-z_{k}\right)\right\rangle \leq 0, . \tag{19}
\end{align*}
$$

Since $z_{k+\frac{1}{2}}=\Pi_{\mathcal{Z}}\left(z_{k}-\eta F\left(z_{k}\right)\right)$ and $z_{k+1}=\Pi_{\mathcal{Z}}\left(z_{k}-\eta F\left(z_{k+\frac{1}{2}}\right)\right)$, we can infer that $z_{k}-$ $\eta F\left(z_{k}\right)-z_{k+\frac{1}{2}} \in N\left(z_{k+\frac{1}{2}}\right)$ and $z_{k}-\eta F\left(z_{k+\frac{1}{2}}\right)-z_{k+1} \in N\left(z_{k+1}\right)$, which further implies

$$
\begin{align*}
& (-2) \cdot\left\langle z_{k}-\eta F\left(z_{k}\right)-z_{k+\frac{1}{2}}, z_{k+\frac{1}{2}}-z_{k+1}\right\rangle \leq 0  \tag{20}\\
& (-2) \cdot\left\langle z_{k}-\eta F\left(z_{k+\frac{1}{2}}\right)-z_{k+1}, z_{k+1}-z_{k}\right\rangle \leq 0  \tag{21}\\
& (-2) \cdot\left\langle\eta c_{k}, z_{k}-z_{k+\frac{1}{2}}\right\rangle \leq 0 \tag{22}
\end{align*}
$$

Since $z_{k}-\eta F\left(z_{k+\frac{1}{2}}\right)-z_{k+1} \in N\left(z_{k+1}\right)$ and $c_{k+1}=\Pi_{N \mathcal{Z}\left(z_{k+1}\right)}\left(-F\left(z_{k+1}\right)\right)$, by Lemma 6 we have

$$
\begin{align*}
& (-2) \cdot\left\langle\eta c_{k+1}+\eta F\left(z_{k+1}\right), z_{k}-\eta F\left(z_{k+\frac{1}{2}}\right)-z_{k+1}\right\rangle \leq 0  \tag{23}\\
& (-2) \cdot\left\langle\eta c_{k+1}+\eta F\left(z_{k+1}\right),-\eta c_{k+1}\right\rangle=0 \tag{24}
\end{align*}
$$

MATLAB code for the verification of the following identity can be found at this link.

$$
\begin{align*}
& \text { Expression (17) + LHS of Inequality (18) }+ \text { LHS of Inequality (19) } \\
& \text { + LHS of Inequality (20) }+ \text { LHS of Inequality (21) }+ \text { LHS of Inequality (22) } \\
& \text { + LHS of Inequality (23) }+ \text { LHS of Inequality (24) } \\
& =\left\|\eta F\left(z_{k}\right)+\eta c_{k}-z_{k}+z_{k+\frac{1}{2}}\right\|^{2}  \tag{25}\\
& +\left\|\eta F\left(z_{k+\frac{1}{2}}\right)+\eta c_{k+1}-z_{k}+z_{k+1}\right\|^{2} \geq 0 \tag{26}
\end{align*}
$$

which concludes the proof.
Theorem 3. Let $\mathcal{Z} \subseteq \mathbb{R}^{n}$ be a closed convex set, $F(\cdot): \mathcal{Z} \rightarrow \mathbb{R}^{n}$ be a monotone and L-Lipschitz operator and $z^{*} \in \mathcal{Z}$ be the solution to the variational inequality. Then for any $T \geq 1, z_{T}$ produced by $E G$ with any constant step size $\eta \in\left(0, \frac{1}{L}\right)$ satisfies

- $\operatorname{GAP}\left(z_{T}\right) \leq \frac{1}{\sqrt{T}} \frac{3 D\left\|z_{0}-z^{*}\right\|}{\eta \sqrt{1-(\eta L)^{2}}}$,
- $r^{n a t}\left(z_{T}\right) \leq r^{t a n}\left(z_{T}\right) \leq \frac{1}{\sqrt{T}} \frac{3\left\|z_{0}-z^{*}\right\|}{\eta \sqrt{1-(\eta L)^{2}}}$.

Theorem 3 is implied by combing Lemma 1, Lemma 2, Lemma 5, Theorem 2 and the fact that $\eta \in\left(0, \frac{1}{L}\right)$. Choosing $\eta$ to be $\frac{1}{2 L}$ and $D=O\left(\left\|z_{0}-z^{*}\right\|\right)$, then $\operatorname{GAP}\left(z_{T}\right)=O\left(\frac{D^{2} L}{\sqrt{T}}\right)$ matching the $\Omega\left(\frac{D^{2} L}{\sqrt{T}}\right)$ lower bound for EG, OGDA, and more generally all p-SCLI algorithms [Golowich et al., 2020b,a] in terms of the dependence on $D, L$, and $T$. Additionally, $r_{\mathcal{Z}, F, D}^{n a t}\left(z_{T}\right)=O\left(\frac{D L}{\sqrt{T}}\right)$, and $r_{\mathcal{Z}, F, D}^{\tan }\left(z_{T}\right)=O\left(\frac{D L}{\sqrt{T}}\right)$, so our upper bounds for both the natural residual and tangent residual also match the $\Omega\left(\frac{D L}{\sqrt{T}}\right)$ lower bounds with respect to natural residual and tangent residual for EG [Golowich et al., 2020b]. This is because both the natural residual and tangent residual are equivalent to the norm of the operator, and [Golowich et al., 2020b] shows that in the unconstrained setting $\left\|F\left(z_{T}\right)\right\|=\Omega\left(\frac{D L}{\sqrt{T}}\right)$.

## 6 Last-Iterate Convergence of OGDA with Constant Step Size

In this section, we show that the OGDA algorithm with constant step size $\eta \in\left(0, \frac{1}{2 L}\right)$ has $O\left(\frac{1}{\sqrt{T}}\right)$ last-iterate convergence rate with respect to the tangent residual or the gap function. The analysis of the OGDA algorithm follows the same steps as in the analysis of the EG algorithm. Compared to the EG algorithm, the last iterate convergence of OGDA follows by builds on the monotonicity and best-iterate convergence of the following potential function

$$
\begin{equation*}
\Phi_{k}=\left\|F\left(z_{k}\right)-F\left(w_{k}\right)\right\|^{2}+r^{\tan }\left(z_{k}\right)^{2} . \tag{27}
\end{equation*}
$$

The potential function can be thought of as the tangent residual $\left(r^{\tan }\left(z_{k}\right)^{2}\right)$ and an extra correction term $\left\|F\left(z_{k}\right)-F\left(w_{k}\right)\right\|^{2}$. The potential function is discovered directly through SOS programming. The SOS program was formulated by searching over linear combinations of $\left\|F\left(z_{k}\right)\right\|^{2}-$ $\left\|F\left(z_{k+1}\right)\right\|^{2},\left\|F\left(w_{k}\right)\right\|^{2}-\left\|F\left(w_{k+1}\right)\right\|^{2},\left\langle F\left(z_{k}\right), F\left(w_{k}\right)\right\rangle-\left\langle F\left(z_{k+1}\right), F\left(w_{k+1}\right)\right\rangle$ and $r^{\tan }\left(z_{k}\right)-r^{\tan }\left(z_{k+1}\right)$, under (i) the constraint that the linear combination is non-increasing, ${ }^{14}$ and (ii) the constraints induced by properties of the operator $F(\cdot)$, the update rule of OGDA and the set $\mathcal{Z}$ (See Figure 5 for a demonstration of the induced constraints of EG algorithm for solving a monotone VI over convex constraints). We then use the linear combination output by the SOS program as the potential function in our analysis. We believe our heuristic for finding a potential function could be useful in other settings. In general, one can first choose a collection of basis functions that may be part of a potential function, then use SOS programming to search over all linear combinations of the basis functions subject to the constraint that the linear combination is non-negative to discover the potential function. We postpone all technical details to Appendix E.

### 6.1 Warm Up: Unconstrained Case

In this section, we show that in the unconstrained setting the potential function $\Phi_{k}$ is nonincreasing, which implies the $O\left(\frac{1}{\sqrt{T}}\right)$ last-iterate convergence rate for OGDA with respect to the tangent residual, the natural residual, and the gap function.
Theorem 4. Let $F: \mathbb{R}^{n} \rightarrow \mathbb{R}^{n}$ be a monotone and L-Lipschitz operator. Then for any $k \in \mathbb{N}$, the OGDA algorithm with step size $\eta \in\left(0, \frac{1}{2 L}\right)$ satisfies $\left\|F\left(z_{k}\right)-F\left(w_{k}\right)\right\|^{2}+\left\|F\left(z_{k}\right)\right\|^{2} \geq\left\|F\left(z_{k+1}\right)-F\left(w_{k+1}\right)\right\|^{2}+$ $\left\|F\left(z_{k+1}\right)\right\|^{2}$.
Proof. Since $F$ is monotone and L-Lipschitz, we have $\left\langle F\left(z_{k+1}\right)-F\left(z_{k}\right), z_{k}-z_{k+1}\right\rangle \leq 0$ and $\left\|F\left(w_{k+1}\right)-F\left(z_{k+1}\right)\right\|^{2}-L^{2}\left\|w_{k+1}-z_{k+1}\right\|^{2} \leq 0$. We simplify them using the update rule of OGDA and $\eta^{2} L^{2}<\frac{1}{4}$. In particular, we replace $z_{k}-z_{k+1}$ by $\eta F\left(w_{k+1}\right)$ and $w_{k+1}-z_{k+1}$ with $\eta F\left(w_{k+1}\right)-\eta F\left(w_{k}\right)$.

$$
\begin{align*}
& \left\langle F\left(z_{k+1}\right)-F\left(z_{k}\right), F\left(w_{k+1}\right)\right\rangle \leq 0  \tag{28}\\
& \left\|F\left(w_{k+1}\right)-F\left(z_{k+1}\right)\right\|^{2}-\frac{1}{4}\left\|F\left(w_{k+1}\right)-F\left(w_{k}\right)\right\|^{2} \leq 0 \tag{29}
\end{align*}
$$

[^14]MATLAB code for the verification of the following identity can be found at this link.

$$
\begin{align*}
& \left\|F\left(z_{k}\right)-F\left(w_{k}\right)\right\|^{2}+\left\|F\left(z_{k}\right)\right\|^{2}-\left\|F\left(z_{k+1}\right)-F\left(w_{k+1}\right)\right\|^{2}-\left\|F\left(z_{k+1}\right)\right\|^{2} \\
& +2 \cdot \operatorname{LHS} \text { of Inequality }(28)+2 \cdot \operatorname{LHS} \text { of Inequality }(29) \\
& \left.=\frac{1}{2} \| F\left(w_{k}\right)+F\left(w_{k+1}\right)-2 F\left(z_{k}\right)\right) \|^{2} . \tag{30}
\end{align*}
$$

Thus, $\left\|F\left(z_{k}\right)-F\left(w_{k}\right)\right\|^{2}+\left\|F\left(z_{k}\right)\right\|^{2} \geq\left\|F\left(z_{k+1}\right)-F\left(w_{k+1}\right)\right\|^{2}+\left\|F\left(z_{k+1}\right)\right\|^{2}$.
The following theorem is a combination of Corollary 2, Theorem 4, Lemma 12, Lemma 1 and Lemma 2.

Theorem 5. Let $F: \mathbb{R}^{n} \rightarrow \mathbb{R}$ be a monotone and L-Lipschitz operator. Let $z_{0}=w_{0} \in \mathbb{R}^{n}$ be arbitrary starting point and $\left\{z_{k}, w_{k}\right\}_{k \geq 0}$ be the iterates of the OGDA algorithm with any step size $\eta \in\left(0, \frac{1}{2 L}\right)$. Denote $D_{0}:=\sqrt{\left(4+6 \eta^{4} L^{4}\right)\left\|z_{0}-z^{*}\right\|^{2}+\left(16 \eta^{2} L^{2}+6 \eta^{4} L^{4}\right)\left\|w_{0}-z_{0}\right\|^{2}}=$ $O\left(\max \left\{\left\|z_{0}-z^{*}\right\|,\left\|w_{0}-z_{0}\right\|\right\}\right)$. Then for any $T \geq 1$,

- $\operatorname{GAP}_{\mathcal{Z}, F, D}\left(z_{T}\right) \leq \frac{1}{\sqrt{T}} \cdot \frac{D D_{0}}{\eta \sqrt{\left.1-4(\eta L)^{2}\right)}}$.
- $r_{\mathcal{Z}, F, D}^{n a t}\left(z_{T}\right) \leq r_{\mathcal{Z}, F, D}^{t a n}\left(z_{T}\right) \leq \frac{1}{\sqrt{T}} \cdot \frac{D_{0}}{\eta \sqrt{1-4(\eta L)^{2}}}$.
- $\operatorname{GAP}_{\mathcal{Z}, F, D}\left(w_{T+1}\right) \leq \frac{1}{\sqrt{T}} \cdot \frac{\sqrt{2}(2+\eta L) \cdot D D_{0}}{\eta \sqrt{1-4(\eta L)^{2}}}$.
- $r_{\mathcal{Z}, F, D}^{n a t}\left(w_{T+1}\right) \leq r_{\mathcal{Z}, F, D}^{\tan }\left(w_{T+1}\right) \leq \frac{1}{\sqrt{T}} \cdot \frac{\sqrt{2}(2+\eta L) \cdot D_{0}}{\eta \sqrt{1-4(\eta L)^{2}}}$.


### 6.2 Last-Iterate Convergence of OGDA with Arbitrary Convex Constraints

In this section, we formally state the last-iterate convergence of OGDA algorithm with respect to the gap function, the natural residual and the tangent residual in the constrained setting. All the details are postponed to Appendix E.
Theorem 6. Let $\mathcal{Z} \subseteq \mathbb{R}^{n}$ be a closed convex set and $F: \mathcal{Z} \rightarrow \mathbb{R}$ be a monotone and L-Lipschitz operator. Let $z_{0}, w_{0} \in \mathcal{Z}$ be arbitrary starting point and $\left\{z_{k}, w_{k}\right\}_{k \geq 0}$ be the iterates of the OGDA algorithm with any step size $\eta \in\left(0, \frac{1}{2 L}\right)$. Let $D_{0}:=\sqrt{\left(4+6 \eta^{4} L^{4}\right)\left\|z_{0}-z^{*}\right\|^{2}+\left(16 \eta^{2} L^{2}+6 \eta^{4} L^{4}\right)\left\|w_{0}-z_{0}\right\|^{2}}=$ $O\left(\max \left\{\left\|z_{0}-z^{*}\right\|,\left\|w_{0}-z_{0}\right\|\right\}\right)$. Then for any $T \geq 1$,

- $\operatorname{GAP}_{\mathcal{Z}, F, D}\left(z_{T}\right) \leq \frac{D D_{0}}{\eta \cdot \sqrt{T \cdot\left(1-4 \cdot(\eta L)^{2}\right)}}$.
- $r_{\mathcal{Z}, F, D}^{n a t}\left(z_{T}\right) \leq r_{\mathcal{Z}, F, D}^{t a n}\left(z_{T}\right) \leq \frac{D_{0}}{\eta \cdot \sqrt{T \cdot\left(1-4 \cdot(\eta L)^{2}\right)}}$.
- $\operatorname{GAP}_{\mathcal{Z}, F, D}\left(w_{T+1}\right) \leq \frac{\sqrt{2}(2+\eta L) \cdot D \cdot D_{0}}{\eta \cdot \sqrt{T \cdot\left(1-4 \cdot(\eta L)^{2}\right)}}$.
- $r_{\mathcal{Z}, F, D}^{n a t}\left(w_{T+1}\right) \leq r_{\mathcal{Z}, F, D}^{t a n}\left(w_{T+1}\right) \leq \frac{\sqrt{2}(2+\eta L) D_{0}}{\eta \cdot \sqrt{T \cdot\left(1-4 \cdot(\eta L)^{2}\right)}}$.

Setting $D=\max \left\{\left\|z_{0}-z^{*}\right\|,\left\|w_{0}-z_{0}\right\|\right\}$, and $\eta=\frac{1}{2 \sqrt{2} L}$, we have $\operatorname{GAP}_{\mathcal{Z}, F, D}\left(z_{T}\right)$ (or $\left.\operatorname{GAP}_{\mathcal{Z}, F, D}\left(w_{T}\right)\right)=O\left(\frac{D^{2} L}{\sqrt{T}}\right)$, which matches the lower bound of $\Omega\left(\frac{D^{2} L}{\sqrt{T}}\right)$ by Golowich et al. [2020a].

## References

Yossi Arjevani and Ohad Shamir. On the iteration complexity of oblivious first-order optimization algorithms. In International Conference on Machine Learning, 2016.

Martin Arjovsky, Soumith Chintala, and Léon Bottou. Wasserstein Generative Adversarial Networks. In Proceedings of the 34th International Conference on Machine Learning, July 2017.

Emil Artin. Über die zerlegung definiter funktionen in quadrate. In Abhandlungen aus dem mathematischen Seminar der Universität Hamburg, volume 5, pages 100-115. Springer, 1927. Issue: 1.

Alfred Auslender and Marc Teboulle. Interior projection-like methods for monotone variational inequalities. Mathematical programming, 104(1):39-68, 2005. Publisher: Springer.

Aharon Ben-Tal, Laurent El Ghaoui, and Arkadi Nemirovski. Robust Optimization. Princeton University Press, December 2009.

Haïm Brezis and Moïse Sibony. Méthodes d'approximation et d'itération pour les opérateurs monotones. Archive for Rational Mechanics and Analysis, 28(1):59-82, January 1968.

Felix E. Browder. Nonlinear monotone operators and convex sets in Banach spaces. Bulletin of the American Mathematical Society, 71(5):780-785, 1965.

Yang Cai and Constantinos Daskalakis. On Minmax Theorems for Multiplayer Games. In Proceedings of the 2011 Annual ACM-SIAM Symposium on Discrete Algorithms (SODA), January 2011.

Yang Cai, Ozan Candogan, Constantinos Daskalakis, and Christos Papadimitriou. Zero-Sum Polymatrix Games: A Generalization of Minmax. Mathematics of Operations Research, 41(2):648-655, May 2016.

Yang Cai, Argyris Oikonomou, and Weiqiang Zheng. Tight last-iterate convergence of the extragradient and the optimistic gradient descent-ascent algorithm for constrained monotone variational inequalities (version 2), 2022. URL https://arxiv. org/abs/2204.09228v2.

Nicolo Cesa-Bianchi and Gabor Lugosi. Prediction, Learning, and Games. Cambridge University Press, 2006.

Tatjana Chavdarova, Gauthier Gidel, François Fleuret, and Simon Lacoste-Julien. Reducing noise in GAN training with variance reduced extragradient. In Advances in Neural Information Processing Systems, volume 32, 2019.

Bo Dai, Albert Shaw, Lihong Li, Lin Xiao, Niao He, Zhen Liu, Jianshu Chen, and Le Song. Sbeed: Convergent reinforcement learning with nonlinear function approximation. In International Conference on Machine Learning, 2018.

Constantinos Daskalakis and Ioannis Panageas. Last-iterate convergence: Zero-sum games and constrained min-max optimization. In 10th Innovations in Theoretical Computer Science Conference, volume 124, pages 27:1-27:18, 2019.

Constantinos Daskalakis, Andrew Ilyas, Vasilis Syrgkanis, and Haoyang Zeng. Training gans with optimism. In 6th International Conference on Learning Representations, 2018.

Jelena Diakonikolas. Halpern iteration for near-optimal and parameter-free monotone inclusion and strong solutions to variational inequalities. In Conference on Learning Theory, 2020.

Radu-Alexandru Dragomir, Adrien B. Taylor, Alexandre d'Aspremont, and Jérôme Bolte. Optimal complexity and certification of bregman first-order methods. Mathematical Programming, 2021.

Yoel Drori and Marc Teboulle. Performance of first-order methods for smooth convex minimization: a novel approach. Mathematical Programming, 145(1):451-482, 2014.

Simon S. Du, Jianshu Chen, Lihong Li, Lin Xiao, and Dengyong Zhou. Stochastic variance reduction methods for policy evaluation. In International Conference on Machine Learning, 2017.

Eyal Even-Dar, Yishay Mansour, and Uri Nadav. On the convergence of regret minimization dynamics in concave games. In Proceedings of the forty-first annual ACM symposium on Theory of computing, pages 523-532, 2009.

Francisco Facchinei and Jong-Shi Pang. Finite-dimensional variational inequalities and complementarity problems. Springer Science \& Business Media, 2007.

Mahyar Fazlyab, Manfred Morari, and Victor M Preciado. Design of first-order optimization algorithms via sum-of-squares programming. In 2018 IEEE Conference on Decision and Control (CDC), pages 4445-4452. IEEE, 2018.

Gauthier Gidel, Hugo Berard, Gaëtan Vignoud, Pascal Vincent, and Simon Lacoste-Julien. A variational inequality perspective on generative adversarial networks. In 7th International Conference on Learning Representations, 2019a.

Gauthier Gidel, Reyhane Askari Hemmat, Mohammad Pezeshki, Rémi Le Priol, Gabriel Huang, Simon Lacoste-Julien, and Ioannis Mitliagkas. Negative momentum for improved game dynamics. In The 22nd International Conference on Artificial Intelligence and Statistics, 2019b.

Noah Golowich, Sarath Pattathil, and Constantinos Daskalakis. Tight last-iterate convergence rates for no-regret learning in multi-player games. In Annual Conference on Neural Information Processing Systems, 2020a.

Noah Golowich, Sarath Pattathil, Constantinos Daskalakis, and Asuman E. Ozdaglar. Last iterate is slower than averaged iterate in smooth convex-concave saddle point problems. In Conference on Learning Theory, 2020b.

Ian J. Goodfellow, Jean Pouget-Abadie, Mehdi Mirza, Bing Xu, David Warde-Farley, Sherjil Ozair, Aaron C. Courville, and Yoshua Bengio. Generative adversarial nets. In Annual Conference on Neural Information Processing Systems, 2014.

Eduard Gorbunov, Nicolas Loizou, and Gauthier Gidel. Extragradient method: O(1/K) last-iterate convergence for monotone variational inequalities and connections with cocoercivity. CoRR, abs/2110.04261, 2021. URL https://arxiv.org/abs/2110.04261.

Baptiste Goujaud, Céline Moucer, François Glineur, Julien M. Hendrickx, Adrien B. Taylor, and Aymeric Dieuleveut. Pepit: computer-assisted worst-case analyses of first-order optimization methods in python. CoRR, abs/2201.04040, 2022. URL https://arxiv.org/abs/2201.04040.

Philip Hartman and Guido Stampacchia. On some non-linear elliptic differential-functional equations. Acta Mathematica, 115:271-310, January 1966.

Yu-Guan Hsieh, Franck Iutzeler, Jérôme Malick, and Panayotis Mertikopoulos. On the convergence of single-call stochastic extra-gradient methods. In Annual Conference on Neural Information Processing Systems, 2019.

Donghwan Kim. Accelerated proximal point method for maximally monotone operators. Mathematical Programming, 190(1):57-87, November 2021.
G. M. Korpelevich. The extragradient method for finding saddle points and other problems. Matecon, 12:747-756, 1976.

Jean-Louis Krivine. Anneaux préordonnés. Journal d'analyse mathématique, 12:p. 307-326, 1964.
Sucheol Lee and Donghwan Kim. Fast extra gradient methods for smooth structured nonconvexnonconcave minimax problems. In Annual Conference on Neural Information Processing Systems, 2021.

Qi Lei, Sai Ganesh Nagarajan, Ioannis Panageas, and Xiao Wang. Last iterate convergence in noregret learning: constrained min-max optimization for convex-concave landscapes. In The 24th International Conference on Artificial Intelligence and Statistics, 2021.

Laurent Lessard, Benjamin Recht, and Andrew Packard. Analysis and Design of Optimization Algorithms via Integral Quadratic Constraints. SIAM Journal on Optimization, 26(1):57-95, January 2016.

Tengyuan Liang and James Stokes. Interaction matters: A note on non-asymptotic local convergence of generative adversarial networks. In The 22nd International Conference on Artificial Intelligence and Statistics, 2019.

Tianyi Lin, Zhengyuan Zhou, Panayotis Mertikopoulos, and Michael I. Jordan. Finite-time lastiterate convergence for multi-agent learning in games. In Proceedings of the 37th International Conference on Machine Learning, 2020.

Jacques-Louis Lions and Guido Stampacchia. Variational inequalities. Communications on pure and applied mathematics, 20(3):493-519, 1967.

Aleksander Madry, Aleksandar Makelov, Ludwig Schmidt, Dimitris Tsipras, and Adrian Vladu. Towards deep learning models resistant to adversarial attacks. In 6th International Conference on Learning Representations, 2018.

Yu Malitsky. Projected Reflected Gradient Methods for Monotone Variational Inequalities. SIAM Journal on Optimization, 25(1):502-520, January 2015.

Panayotis Mertikopoulos, Christos Papadimitriou, and Georgios Piliouras. Cycles in adversarial regularized learning. In Proceedings of the Twenty-Ninth Annual ACM-SIAM Symposium on Discrete Algorithms, pages 2703-2717, 2018.

Aryan Mokhtari, Asuman E. Ozdaglar, and Sarath Pattathil. A unified analysis of extra-gradient and optimistic gradient methods for saddle point problems: Proximal point approach. In The 23rd International Conference on Artificial Intelligence and Statistics, 2020.

Renato DC Monteiro and Benar Fux Svaiter. On the Complexity of the Hybrid Proximal Extragradient Method for the Iterates and the Ergodic Mean. SIAM Journal on Optimization, 20(6): 2755-2787, January 2010.

Arkadi Nemirovski. Prox-method with rate of convergence $O(1 / t)$ for variational inequalities with Lipschitz continuous monotone operators and smooth convex-concave saddle point problems. SIAM Journal on Optimization, 15(1):229-251, 2004.

Wei Peng, Yu-Hong Dai, Hui Zhang, and Lizhi Cheng. Training GANs with centripetal acceleration. Optimization Methods and Software, 35(5):955-973, 2020.

Leonid Denisovich Popov. A modification of the Arrow-Hurwicz method for search of saddle points. Mathematical notes of the Academy of Sciences of the USSR, 28(5):845-848, 1980.

Alexander Rakhlin and Karthik Sridharan. Online Learning with Predictable Sequences. In Conference on Learning Theory, June 2013.

Ernest K. Ryu, Adrien B. Taylor, Carolina Bergeling, and Pontus Giselsson. Operator splitting performance estimation: Tight contraction factors and optimal parameter selection. SIAM Journal on Optimization, 30(3):2251-2271, 2020.

Shai Shalev-Shwartz et al. Online learning and online convex optimization. Foundations and Trends ${ }^{\circledR}$ in Machine Learning, 4(2):107-194, 2012.

Moïse Sibony. Méthodes itératives pour les équations et inéquations aux dérivées partielles non linéaires de type monotone. CALCOLO, 7(1):65-183, March 1970.

Gilbert Stengle. A nullstellensatz and a positivstellensatz in semialgebraic geometry. Mathematische Annalen, 207(2):87-97, June 1974.

Sandra SY Tan, Antonios Varvitsiotis, and Vincent YF Tan. Analysis of optimization algorithms via sum-of-squares. Journal of Optimization Theory and Applications, 190(1):56-81, 2021.

Adrien B. Taylor, Julien M. Hendrickx, and François Glineur. Exact Worst-case Performance of First-order Methods for Composite Convex Optimization. SIAM Journal on Optimization, 27(3): 1283-1313, January 2017a.
Adrien B. Taylor, Julien M. Hendrickx, and François Glineur. Performance estimation toolbox (PESTO): automated worst-case analysis of first-order optimization methods. In 2017 IEEE 56th Annual Conference on Decision and Control (CDC), 2017b.

Paul Tseng. On linear convergence of iterative methods for the variational inequality problem. Journal of Computational and Applied Mathematics, 60(1):237-252, June 1995. ISSN 0377-0427.

Paul Tseng. On accelerated proximal gradient methods for convex-concave optimization. submitted to SIAM Journal on Optimization, 2(3), 2008.

Chen-Yu Wei, Chung-Wei Lee, Mengxiao Zhang, and Haipeng Luo. Last-iterate convergence of decentralized optimistic gradient descent/ascent in infinite-horizon competitive markov games. In Conference on Learning Theory, 2021a.

Chen-Yu Wei, Chung-Wei Lee, Mengxiao Zhang, and Haipeng Luo. Linear last-iterate convergence in constrained saddle-point optimization. In 9th International Conference on Learning Representations, 2021b.

Abhay Kumar Yadav, Sohil Shah, Zheng Xu, David W. Jacobs, and Tom Goldstein. Stabilizing adversarial nets with prediction methods. In 6th International Conference on Learning Representations, 2018.

Taeho Yoon and Ernest K. Ryu. Accelerated algorithms for smooth convex-concave minimax problems with $\mathrm{o}\left(1 / \mathrm{k}^{\wedge} 2\right)$ rate on squared gradient norm. In Proceedings of the 38th International Conference on Machine Learning, 2021.

Guodong Zhang, Xuchan Bao, Laurent Lessard, and Roger B. Grosse. A unified analysis of firstorder methods for smooth games via integral quadratic constraints. Journal of Machine Learning Research, 22:103:1-103:39, 2021.

Guojun Zhang and Yaoliang Yu. Convergence of gradient methods on bilinear zero-sum games. In 8th International Conference on Learning Representations, 2020.

## A Additional Preliminaries

For $z \in \mathbb{R}^{n}$ and $D>0$, we use $\mathcal{B}(z, D)=\left\{z^{\prime} \in R^{n}:\left\|z^{\prime}-z\right\| \leq R\right\}$ to denote the ball of radius $D$, centered at $z$.

Min-Max Saddle Points. A special case of the variational inequality problem is the constrained min-max problem $\min _{x \in \mathcal{X}} \max _{y \in \mathcal{Y}} f(x, y)$, where $\mathcal{X}$ and $\mathcal{Y}$ are closed convex sets in $\mathbb{R}^{n}$, and $f(\cdot, \cdot)$ is smooth, convex in $x$, and concave in $y$. It is well known that if one set $F(x, y)=\binom{\nabla_{x} f(x, y)}{-\nabla_{y} f(x, y)}$, then $F(x, y)$ is a monotone and Lipschitz operator [Facchinei and Pang, 2007].

Equilibria of Monotone Games. Monotone games are a large class of multi-player games that include many common and well-studied class of games such as bilinear games, $\lambda$-cocoercive games [Lin et al., 2020], zero-sum polymatrix games [Cai and Daskalakis, 2011, Cai et al., 2016], and zero-sum socially-concave games [Even-Dar et al., 2009]. Besides, the min-max saddle point problem is a special case of two-player monotone games. We include the definition of monotone games here and remind readers that finding a Nash Equilibrium of a monotone game is exactly the same as finding a solution to a monotone variational inequality.

A continuous game $\mathcal{G}$ is denoted as $\left(\mathcal{N},\left(\mathcal{X}_{i}\right)_{i \in[N]},\left(f_{i}\right)_{i \in[N]}\right)$ where there are $N$ players $\mathcal{N}=$ $\{1, \cdots, N\}$. Player $i \in \mathcal{N}$ chooses action from a closed convex set $\mathcal{X}_{i} \in \mathbb{R}^{n_{i}}$ such that $\mathcal{X}:=$ $\Pi_{i \in \mathcal{N}} \mathcal{X}_{i} \in \mathbb{R}^{n}$ and wants to minimize its cost function $f_{i}: \mathcal{X} \rightarrow \mathbb{R}$. For each player $i$, we denote $x_{-i}$ the vector of actions of all the other players. A Nash Equilibrium of game $\mathcal{G}$ is an action profile $x^{*} \in \mathcal{X}$ such that $f_{i}\left(x^{*}\right) \leq f_{i}\left(x_{i}^{\prime}, x_{-i}^{*}\right)$ for any $x_{i}^{\prime} \in \mathcal{X}_{i}$. Let $F(x)=\left(\nabla_{x_{i}} f_{i}(x), \cdots, \nabla_{x_{N}} f_{N}(x)\right) \in \mathbb{R}^{n}$. We say $\mathcal{G}$ is monotone if $\left\langle F(x)-F\left(x^{\prime}\right), x-x^{\prime}\right\rangle \geq 0$ for any $x, x^{\prime} \in \mathcal{X}$.

In Lemma 7 we present several equivalent formulations of the tangent residual.
Lemma 7. Let $\mathcal{Z}$ be a closed convex set and $F: \mathcal{Z} \rightarrow \mathbb{R}^{n}$ be an operator. Denote $N_{\mathcal{Z}}(z)$ the normal cone of $z$ and $J_{\mathcal{Z}}(z):=\{z\}+T_{\mathcal{Z}}(z)$, where $T_{\mathcal{Z}}(z)=\left\{z^{\prime} \in \mathbb{R}^{n}:\left\langle z^{\prime}, a\right\rangle \leq 0, \forall a \in N_{\mathcal{Z}}(z)\right\}$ is the tangent cone of $z$. Then all of the following quantities are equivalent:

1. $\sqrt{\|F(z)\|^{2}-\max _{\substack{a \in \widehat{N}_{\mathcal{Z}}(z),\langle F(z), a\rangle \leq 0}}\langle F(z), a\rangle^{2}}$
2. $\min _{a \in \widehat{N}_{\mathcal{Z}}(z),}\|F(z)-\langle F(z), a\rangle \cdot a\|$ $\langle F(z), a\rangle \leq 0$
3. $\left\|\Pi_{T_{\mathcal{Z}}(z)}[-F(z)]\right\|$
4. $\left\|\Pi_{J z(z)}[z-F(z)]-z\right\|$
5. $\left\|-F(z)-\Pi_{N_{\mathcal{Z}}(z)}[-F(z)]\right\|$
6. $\min _{a \in N_{\mathcal{Z}}(z)}\|F(z)+a\|$

Proof. (quantity $\mathbf{1}$ = quantity $\mathbf{2}$ ). Observe that

$$
\min _{\substack{a \in \widehat{N} \mathcal{Z}(z),\langle F(z), a\rangle \leq 0}}\|F(z)-\langle F(z), a\rangle \cdot a\|^{2}=\|F(z)\|^{2}-\max _{\substack{a \in \widehat{N}_{\mathcal{Z}}(z),\langle F(z), a\rangle \leq 0}}\langle F(z), a\rangle^{2} \cdot\left(2-\|a\|^{2}\right) .
$$

Therefore, it is enough to show that $\max _{\substack{a \in \widehat{N}_{z}(z),\langle F(z), a\rangle \leq 0}}\langle F(z), a\rangle^{2} \cdot\left(2-\|a\|^{2}\right)=$ $\max _{a \in \widehat{N}_{\mathcal{Z}}(z),\langle }\langle F(z), a\rangle^{2}$. If $\widehat{N}_{\mathcal{Z}}(z)=\{(0, \ldots, 0)\}$, then the equality holds trivially. Now we $\langle F(z), a\rangle \leq 0$
assume that $\{(0, \ldots, 0)\} \subsetneq \widehat{N}_{\mathcal{Z}}(z)$ and consider any $a \in \widehat{N}_{\mathcal{Z}}(z) \backslash(0, \ldots, 0)$. Let $c \in\left[1, \frac{1}{\|a\|}\right]$. By Definition $2,\|a\| \leq 1$, which implies that $c \cdot a \in \widehat{N}_{\mathcal{Z}}(z)$. We try to maximize the following objective

$$
\langle F(z), c \cdot a\rangle^{2} \cdot\left(2-c^{2}\|a\|^{2}\right)=\frac{\langle F(z), a\rangle^{2}}{\|a\|^{2}} \cdot c^{2}\|a\|^{2} \cdot\left(2-c^{2}\|a\|^{2}\right) .
$$

One can easily verify that function $c^{2}\|a\|^{2} \cdot\left(2-c^{2}\|a\|^{2}\right)$ is maximized when $c^{2}\|a\|^{2}=1 \Leftrightarrow c=$ $\frac{1}{\|a\| \|}$. Thus when $\{(0, \ldots, 0)\} \subsetneq \widehat{N}_{\mathcal{Z}}(z)$,

$$
\begin{aligned}
\max _{\substack{a \in \widehat{\mathcal{N}}_{z}(z),\langle F(z), a\rangle \leq 0}}\langle F(z), a\rangle^{2} \cdot\left(2-\|a\|^{2}\right) & =\max _{\substack{a \in \widehat{\mathcal{N}}_{z}(z),\langle F(z), a\rangle \leq 0,\|a\|=1}}\langle F(z), a\rangle^{2} \cdot\left(2-\|a\|^{2}\right) \\
& =\max _{\substack{a \in \widehat{\widehat{z}}_{z}(z),\langle F(z), a\rangle, 0 \\
\|a\|=1}}\langle F(z), a\rangle^{2} \\
& =\max _{\substack{a \in \widehat{N}_{z}(z),\langle F(z), a\rangle \leq 0}}\langle F(z), a\rangle^{2},
\end{aligned}
$$

which concludes the proof.
(quantity 3 = quantity 4). By definition, $J_{\mathcal{Z}}(z)=\{z\}+T_{\mathcal{Z}}(z)$. Thus we have

$$
\left\|\Pi_{J_{\mathcal{Z}}(z)}[z-F(z)]-z\right\|=\left\|\Pi_{T_{\mathcal{Z}}(z)}[-F(z)]\right\| .
$$

(quantity 4 = quantity 5). By definition, the tangent cone $T_{\mathcal{Z}}(z)$ is the polar cone of the normal cone $N_{\mathcal{Z}}(z)$. Since $N_{\mathcal{Z}}(z)$ is a closed convex cone, by Moreau's decomposition theorem, we have for any vector $x \in \mathbb{R}^{n}$,

$$
x=\Pi_{N_{\mathcal{Z}}(z)}(x)+\Pi_{T_{\mathcal{Z}}(z)}(x), \quad\left\langle\Pi_{N_{\mathcal{Z}}(z)}(x), \Pi_{T_{\mathcal{Z}}(z)}(x)\right\rangle=0
$$

Thus it is clear that we have

$$
\begin{aligned}
\left\|\Pi_{J \mathcal{Z}(z)}[z-F(z)]-z\right\| & =\left\|\Pi_{T_{\mathcal{Z}}(z)}[-F(z)]\right\| \\
& =\left\|-F(z)-\Pi_{N_{\mathcal{Z}}(z)}[-F(z)]\right\| .
\end{aligned}
$$

(quantity 5 = quantity 6). Denote $a^{*}:=\Pi_{N_{\mathcal{Z}}(z)}[-F(z)]$. By definition of projection, we have

$$
a^{*}=\underset{a \in N_{\mathcal{Z}}(z)}{\operatorname{argmin}}\|F(z)+a\|^{2} .
$$

Thus

$$
\left\|-F(z)-\Pi_{N_{\mathcal{Z}}(z)}[-F(z)]\right\|^{2}=\left\|F(z)+a^{*}\right\|^{2}=\min _{a \in N_{\mathcal{Z}}(z)}\|F(z)+a\|^{2}
$$

(quantity 6 = quantity 2). For any fix non-zero $a \in N_{\mathcal{Z}}(z)$, (i) if $\langle F(z), a\rangle>0$, then $\|F(z)+a\|^{2} \geq$ $\|F(z)\|^{2}$, and (ii) if $\langle F(z), a\rangle \leq 0,\|F(z)+a\|^{2} \geq\left\|F(z)-\left\langle F(z), \frac{a}{\|a\|}\right\rangle \cdot \frac{a}{\|a\|}\right\|^{2}$, as

$$
\min _{r \geq 0}\|F(z)+r \cdot a\|^{2}=\left\|F(z)-\left\langle F(z), \frac{a}{\|a\|}\right\rangle \cdot \frac{a}{\|a\|}\right\|^{2}
$$

Hence,

$$
\min _{a \in N_{\mathcal{Z}}(z)}\|F(z)+a\|^{2}=\min _{\substack{a^{\prime} \in \hat{N}_{z}(z) \\\left\langle F(z), a^{\prime}\right\rangle \leq 0}}\left\|F(z)-\left\langle F(z), a^{\prime}\right\rangle \cdot a^{\prime}\right\|^{2}
$$

The first equality is because for any $a \in N_{\mathcal{Z}}(z)$, there exists $a^{\prime} \in \widehat{N}_{\mathcal{Z}}(z)$ so that $\|F(z)+a\|^{2} \geq$ $\left\|F(z)-\left\langle F(z), a^{\prime}\right\rangle\right\|^{2}$.

In the following Lemma, we show a useful property of the tangent residual that we use repeatedly.
Lemma 8. Let $\mathcal{Z} \subseteq \mathbb{R}^{n}$ be a closed convex set and $F: \mathcal{Z} \rightarrow \mathbb{R}$ be an operator. Let $\eta>0$ and $z_{1}, z_{2}, z_{3} \in \mathcal{Z}$ be three points such that $z_{1}=\Pi_{\mathcal{Z}}\left[z_{2}-\eta F\left(z_{3}\right)\right]$, then we have

$$
r^{\tan }\left(z_{1}\right) \leq\left\|\frac{z_{2}-z_{1}}{\eta}+F\left(z_{1}\right)-F\left(z_{3}\right)\right\| .
$$

Proof. If $z_{1}=z_{2}-\eta F\left(z_{3}\right)$, then the lemma holds since

$$
r^{\tan }\left(z_{1}\right) \leq\left\|F\left(z_{1}\right)\right\|=\left\|F\left(z_{3}\right)+F\left(z_{1}\right)-F\left(z_{3}\right)\right\|=\left\|\frac{z_{2}-z_{1}}{\eta}+F\left(z_{1}\right)-F\left(z_{3}\right)\right\| .
$$

For the rest of the proof, we assume that $z_{1} \neq z_{2}-\eta F\left(z_{3}\right)$. Since $z_{2}-\eta F\left(z_{3}\right)-z_{1} \in N\left(z_{1}\right)$, we have

$$
\left\langle z_{2}-\eta F\left(z_{3}\right)-z_{1}, z-z_{1}\right\rangle \leq 0, \quad \forall z \in \mathcal{Z}
$$

Define $a:=\frac{z_{2}-\eta F\left(z_{3}\right)-z_{1}}{\left\|z_{2}-\eta F\left(z_{3}\right)-z_{1}\right\|}$. We thus know $a \in \widehat{N}\left(z_{1}\right)$. Let

$$
a_{\perp}:= \begin{cases}\frac{F\left(z_{1}\right)-\left\langle a, F\left(z_{1}\right)\right\rangle \cdot a}{\left\|F\left(z_{1}\right)-\left\langle a, F\left(z_{1}\right)\right\rangle \cdot a\right\|} & \text { if }\left\|F\left(z_{1}\right)-\left\langle a, F\left(z_{1}\right)\right\rangle \cdot a\right\| \neq 0 \\ (0, \ldots, 0) & \text { otherwise }\end{cases}
$$

Observe that $\langle a, a\rangle=1,\left\langle a_{\perp}, a\right\rangle=0$ and $F\left(z_{1}\right)=\left\langle a, F\left(z_{1}\right)\right\rangle a+\left\langle a_{\perp}, F\left(z_{1}\right)\right\rangle a_{\perp}$. Thus

$$
\begin{align*}
0=\left\langle a_{\perp}, a\right\rangle & =\left\langle a_{\perp}, z_{2}-\eta F\left(z_{3}\right)-z_{1}\right\rangle \\
\Leftrightarrow\left\langle a_{\perp}, F\left(z_{3}\right)\right\rangle & =\frac{\left\langle a_{\perp}, z_{2}-z_{1}\right\rangle}{\eta} . \tag{31}
\end{align*}
$$

Moreover, the fact that $\left\langle a, z_{1}-z_{2}+\eta F\left(z_{3}\right)\right\rangle \leq 0$ implies $\left\langle a, F\left(z_{3}\right)\right\rangle \leq \frac{\left\langle a, z_{2}-z_{1}\right\rangle}{\eta}$, which further implies that

$$
\begin{equation*}
\left\langle a, F\left(z_{1}\right)\right\rangle=\left\langle a, F\left(z_{3}\right)+F\left(z_{1}\right)-F\left(z_{3}\right)\right\rangle \leq\left\langle a, \frac{z_{2}-z_{1}}{\eta}+F\left(z_{1}\right)-F\left(z_{3}\right)\right\rangle . \tag{32}
\end{equation*}
$$

Combining the definition of $r^{\tan }\left(z_{1}\right)$, Equation (31), and Equation (32) we have

$$
\begin{aligned}
r^{\tan }\left(z_{1}\right)^{2} & \leq\left\|F\left(z_{1}\right)\right\|^{2}-\left\langle a, F\left(z_{1}\right)\right\rangle^{2} \cdot \mathbb{1}\left[\left\langle a, F\left(z_{1}\right)\right\rangle \leq 0\right] \\
& =\left\langle a_{\perp}, F\left(z_{1}\right)\right\rangle^{2}+\left\langle a, F\left(z_{1}\right)\right\rangle^{2} \cdot \mathbb{1}\left[\left\langle a, F\left(z_{1}\right)\right\rangle>0\right] \\
& =\left\langle a_{\perp}, F\left(z_{3}\right)+F\left(z_{1}\right)-F\left(z_{3}\right)\right\rangle^{2}+\left\langle a, F\left(z_{1}\right)\right\rangle^{2} \cdot \mathbb{1}\left[\left\langle a, F\left(z_{1}\right)\right\rangle>0\right] \\
& \leq\left\langle a_{\perp}, \frac{z_{2}-z_{1}}{\eta}+F\left(z_{1}\right)-F\left(z_{3}\right)\right\rangle^{2}+\left\langle a, \frac{z_{2}-z_{1}}{\eta}+F\left(z_{1}\right)-F\left(z_{3}\right)\right\rangle^{2} \\
& \leq\left\|\frac{z_{2}-z_{1}}{\eta}+F\left(z_{1}\right)-F\left(z_{3}\right)\right\|^{2} .
\end{aligned}
$$

Proof of Lemma 2: If $\langle a, F(z)\rangle \geq 0$ for all $a \in \widehat{N}(z)$, then we have $r^{\text {tan }}(z)=\|F(z)\|$. Thus for any $z^{\prime} \in \mathcal{Z}$, by Cauchy-Schwarz inequality, we have

$$
\left\langle F(z), z-z^{\prime}\right\rangle \leq\|F(z)\|\left\|z-z^{\prime}\right\| \leq D \cdot r^{t a n}(z) .
$$

Otherwise there exists $a \in \widehat{N}(z)$ such that $\|a\|=1,\langle a, F(z)\rangle<0$ and $r^{\tan }(z)=$ $\sqrt{\|F(z)\|^{2}-\langle a, F(z)\rangle^{2}}=\|F(z)-\langle a, F(z)\rangle a\|$. Then for any $z^{\prime} \in \mathcal{Z}$, we have

$$
\begin{aligned}
\left\langle F(z), z-z^{\prime}\right\rangle & =\left\langle F(z)-\langle a, F(z)\rangle a, z-z^{\prime}\right\rangle+\langle a, F(z)\rangle \cdot\left\langle a, z-z^{\prime}\right\rangle \\
& \leq\left\langle F(z)-\langle a, F(z)\rangle a, z-z^{\prime}\right\rangle \\
& \leq\|F(z)-\langle a, F(z)\rangle a\|\left\|z-z^{\prime}\right\| \\
& \leq D \cdot r^{\text {tan }}(z),
\end{aligned}
$$

where we use $\langle a, F(z)\rangle<0$ and $\left\langle a, z-z^{\prime}\right\rangle \geq 0$ in the first inequality and Cauchy-Schwarz inequality in the second inequality.

If $\mathcal{Z}^{\prime}=\mathcal{X}^{\prime} \times \mathcal{Y}^{\prime}$ and $F(x, y)=\binom{\nabla_{x} f(x, y)}{-\nabla_{y} f(x, y)}$ for a convex-concave function $f$ then

$$
\begin{aligned}
\operatorname{dg}_{f}^{\mathcal{X}^{\prime}, \mathcal{Y}^{\prime}}(z) & =\max _{y^{\prime} \in \mathcal{Y}^{\prime}} f\left(x, y^{\prime}\right)-\min _{x^{\prime} \in \mathcal{X}^{\prime}} f\left(x^{\prime}, y\right) \\
& =\max _{y^{\prime} \in \mathcal{Y}^{\prime}}\left(f\left(x, y^{\prime}\right)-f(x, y)\right)-\min _{x^{\prime} \in \mathcal{X}^{\prime}}\left(f\left(x^{\prime}, y\right)-f(x, y)\right), \\
& \leq \max _{y^{\prime} \in \mathcal{Y}^{\prime}}\left\langle\nabla_{y} f(x, y), y^{\prime}-y\right\rangle+\max _{x^{\prime} \in \mathcal{X}^{\prime}}\left\langle\nabla_{x} f(x, y), x-x^{\prime}\right\rangle, \\
& =\max _{z^{\prime} \in \mathcal{Z}^{\prime}}\left\langle F(z), z-z^{\prime}\right\rangle, \\
& \leq D \sqrt{2} \cdot r^{\text {tan }}(z),
\end{aligned}
$$

where we use the fact that $f$ is a convex-concave function in the first inequality and $\left\|z-z^{\prime}\right\|=$ $\sqrt{\left\|x-x^{\prime}\right\|^{2}+\left\|y-y^{\prime}\right\|^{2}} \leq \sqrt{2} D$ in the second inequality.

## B Missing Proofs from Section 4

Proof of Lemma 3: By Pythagorean inequality,

$$
\begin{align*}
\left\|z_{k+1}-z^{*}\right\|^{2} & \leq\left\|z_{k}-\eta F\left(z_{k+\frac{1}{2}}\right)-z^{*}\right\|^{2}-\left\|z_{k}-\eta F\left(z_{k+\frac{1}{2}}\right)-z_{k+1}\right\|^{2} \\
& =\left\|z_{k}-z^{*}\right\|^{2}-\left\|z_{k}-z_{k+1}\right\|^{2}+2 \eta\left\langle F\left(z_{k+\frac{1}{2}}\right), z^{*}-z_{k+1}\right\rangle \\
& =\left\|z_{k}-z^{*}\right\|^{2}-\left\|z_{k}-z_{k+1}\right\|^{2}+2 \eta\left\langle F\left(z_{k+\frac{1}{2}}\right), z^{*}-z_{k+\frac{1}{2}}\right\rangle+2 \eta\left\langle F\left(z_{k+\frac{1}{2}}\right), z_{k+\frac{1}{2}}-z_{k+1}\right\rangle . \tag{33}
\end{align*}
$$

We first use monotonicity of $F(\cdot)$ to argue that $\left\langle F\left(z_{k+\frac{1}{2}}\right), z^{*}-z_{k+\frac{1}{2}}\right\rangle \leq 0$.
Fact 1. For all $z \in \mathcal{Z},\left\langle F(z), z^{*}-z\right\rangle \leq 0$.
Proof.

$$
\begin{array}{rlrl}
0 & \leq\left\langle F\left(z^{*}\right)-F(z), z^{*}-z\right\rangle & \text { (monotonicity of } F(\cdot)) \\
& =\left\langle F\left(z^{*}\right), z^{*}-z\right\rangle-\left\langle F(z), z^{*}-z\right\rangle & & \\
& \leq-\left\langle F(z), z^{*}-z\right\rangle & \text { (optimality of } \left.z^{*} \text { and } z \in \mathcal{Z}\right)
\end{array}
$$

We can simplify Equation (33) using Fact 1:

$$
\begin{aligned}
&\left\|z_{k+1}-z^{*}\right\|^{2} \leq\left\|z_{k}-z^{*}\right\|^{2}-\left\|z_{k}-z_{k+1}\right\|^{2}+2 \eta\left\langle F\left(z_{k+\frac{1}{2}}\right), z_{k+\frac{1}{2}}-z_{k+1}\right\rangle \\
&=\left\|z_{k}-z^{*}\right\|^{2}-\left\|z_{k}-z_{k+\frac{1}{2}}\right\|^{2}-\left\|z_{k+\frac{1}{2}}-z_{k+1}\right\|^{2}-2\left\langle z_{k}-\eta F\left(z_{k+\frac{1}{2}}\right)-z_{k+\frac{1}{2}}, z_{k+\frac{1}{2}}-z_{k+1}\right\rangle \\
&=\left\|z_{k}-z^{*}\right\|^{2}-\left\|z_{k}-z_{k+\frac{1}{2}}\right\|^{2}-\left\|z_{k+\frac{1}{2}}-z_{k+1}\right\|^{2} \\
& \quad-2\left\langle z_{k}-\eta F\left(z_{k}\right)-z_{k+\frac{1}{2}}, z_{k+\frac{1}{2}}-z_{k+1}\right\rangle-2\left\langle\eta F\left(z_{k}\right)-\eta F\left(z_{k+\frac{1}{2}}\right), z_{k+\frac{1}{2}}-z_{k+1}\right\rangle \\
& \leq\left\|z_{k}-z^{*}\right\|^{2}-\left\|z_{k}-z_{k+\frac{1}{2}}\right\|^{2}-\left\|z_{k+\frac{1}{2}}-z_{k+1}\right\|^{2}-2 \eta\left\langle F\left(z_{k}\right)-F\left(z_{k+\frac{1}{2}}\right), z_{k+\frac{1}{2}}-z_{k+1}\right\rangle
\end{aligned}
$$

The last inequality is because $\left\langle z_{k}-\eta F\left(z_{k}\right)-z_{k+\frac{1}{2}}, z_{k+\frac{1}{2}}-z_{k+1}\right\rangle \geq 0$, which follows from the that fact that $z_{k+\frac{1}{2}}=\Pi_{\mathcal{Z}}\left[z_{k}-\eta F\left(z_{k}\right)\right]$ and $z_{k+1} \in \mathcal{Z}$.

Finally, since $F(\cdot)$ is $L$-Lipschitz, we know that

$$
-\left\langle F\left(z_{k}\right)-F\left(z_{k+\frac{1}{2}}\right), z_{k+\frac{1}{2}}-z_{k+1}\right\rangle \leq\left\|F\left(z_{k}\right)-F\left(z_{k+\frac{1}{2}}\right)\right\| \cdot\left\|z_{k+\frac{1}{2}}-z_{k+1}\right\| \leq L\left\|z_{k}-z_{k+\frac{1}{2}}\right\| \cdot\left\|z_{k+\frac{1}{2}}-z_{k+1}\right\| .
$$

So we can further simplify the inequality as follows:

$$
\begin{aligned}
\left\|z_{k+1}-z^{*}\right\|^{2} & \leq\left\|z_{k}-z^{*}\right\|^{2}-\left\|z_{k}-z_{k+\frac{1}{2}}\right\|^{2}-\left\|z_{k+\frac{1}{2}}-z_{k+1}\right\|^{2}-2 \eta\left\langle F\left(z_{k}\right)-F\left(z_{k+\frac{1}{2}}\right), z_{k+\frac{1}{2}}-z_{k+1}\right\rangle \\
& \leq\left\|z_{k}-z^{*}\right\|^{2}-\left\|z_{k}-z_{k+\frac{1}{2}}\right\|^{2}-\left\|z_{k+\frac{1}{2}}-z_{k+1}\right\|^{2}+2 \eta L\left\|z_{k}-z_{k+\frac{1}{2}}\right\| \cdot\left\|z_{k+\frac{1}{2}}-z_{k+1}\right\| \\
& \leq\left\|z_{k}-z^{*}\right\|^{2}-\left(1-\eta^{2} L^{2}\right)\left\|z_{k}-z_{k+\frac{1}{2}}\right\|^{2}
\end{aligned}
$$

Hence,

$$
\left\|z_{k}-z^{*}\right\|^{2} \geq\left\|z_{k+1}-z^{*}\right\|^{2}+\left(1-\eta^{2} L^{2}\right)\left\|z_{k}-z_{k+\frac{1}{2}}\right\|^{2}
$$

Proof of Lemma 4: We need the following fact for our proof.
Fact 2. $\left\|z_{k+\frac{1}{2}}-z_{k+1}\right\| \leq \eta L\left\|z_{k}-z_{k+\frac{1}{2}}\right\|$. Moreover, when $\eta L<1,\left\|z_{k+\frac{1}{2}}-z_{k+1}\right\| \leq \frac{\left\|z_{k}-z_{k+1}\right\|}{1-\eta L}$.
Proof. Recall that $z_{k+\frac{1}{2}}=\Pi_{\mathcal{Z}}\left[z_{k}-\eta F\left(z_{k}\right)\right]$ and $z_{k+1}=\Pi_{\mathcal{Z}}\left[z_{k}-\eta F\left(z_{k+\frac{1}{2}}\right)\right]$. By the nonexpansiveness of the projection operator and the L-Lipschitzness of operator $F$, we have that $\left\|z_{k+\frac{1}{2}}-z_{k+1}\right\| \leq\left\|\eta\left(F\left(z_{k+\frac{1}{2}}\right)-F\left(z_{k}\right)\right)\right\| \leq \eta L\left\|z_{k}-z_{k+\frac{1}{2}}\right\|$.

Finally, by the triangle inequality

$$
\left\|z_{k}-z_{k+1}\right\| \geq\left\|z_{k}-z_{k+\frac{1}{2}}\right\|-\left\|z_{k+\frac{1}{2}}-z_{k+1}\right\| \geq(1-\eta L)\left\|z_{k}-z_{k+\frac{1}{2}}\right\|
$$

Now we prove Lemma 4. By the $L$-Lipschitzness of operator $F$ we have

$$
\begin{equation*}
\left\|F\left(z_{k+1}\right)-F\left(z_{k+\frac{1}{2}}\right)\right\| \leq L\left\|z_{k+1}-z_{k+\frac{1}{2}}\right\| \leq \eta L^{2}\left\|z_{k}-z_{k+\frac{1}{2}}\right\| . \tag{34}
\end{equation*}
$$

Recall that $z_{k+1}=\Pi_{\mathcal{Z}}\left[z_{k}-\eta F\left(z_{k+\frac{1}{2}}\right)\right]$. Using Lemma 8, we have

$$
\begin{aligned}
r^{\tan }\left(z_{k+1}\right) & \leq\left\|\frac{z_{k}-z_{k+1}}{\eta}+F\left(z_{k+1}\right)-F\left(z_{k+\frac{1}{2}}\right)\right\| \\
& \leq \frac{\left\|z_{k}-z_{k+1}\right\|}{\eta}+\left\|F\left(z_{k+1}\right)-F\left(z_{k+\frac{1}{2}}\right)\right\| \\
& \leq \frac{\left\|z_{k}-z_{k+1}\right\|+(\eta L)^{2}\left\|z_{k}-z_{k+\frac{1}{2}}\right\|}{\eta} \\
& \leq \frac{\left\|z_{k}-z_{k+\frac{1}{2}}\right\|+\left\|z_{k+\frac{1}{2}}-z_{k+1}\right\|+(\eta L)^{2}\left\|z_{k}-z_{k+\frac{1}{2}}\right\|}{\eta} \\
& \leq\left(1+\eta L+(\eta L)^{2}\right) \frac{\left\|z_{k}-z_{k+\frac{1}{2}}\right\|}{\eta} .
\end{aligned}
$$

The second and the fourth inequality follow from the triangle inequality. The third inequality follows from Equation (34). In the final inequality we use $\left\|z_{k+\frac{1}{2}}-z_{k+1}\right\| \leq \eta L\left\|z_{k}-z_{k+\frac{1}{2}}\right\|$ by Fact 2.
Proof of Lemma 5: By Lemma 3 we have

$$
\left\|z_{0}-z^{*}\right\|^{2} \geq\left\|z_{T+1}-z^{*}\right\|^{2}+\left(1-\eta^{2} L^{2}\right) \sum_{k=0}^{T}\left\|z_{k}-z_{k+\frac{1}{2}}\right\|^{2} \geq\left(1-\eta^{2} L^{2}\right) \sum_{k=0}^{T}\left\|z_{k}-z_{k+\frac{1}{2}}\right\|^{2}
$$

Thus there exists a $t^{*} \in[T]$ such that $\left\|z_{t^{*}}-z_{t^{*}+\frac{1}{2}}\right\|^{2} \leq \frac{\left\|z_{0}-z^{*}\right\|^{2}}{T\left(1-\eta^{2} L^{2}\right)}$. We conclude the proof by applying Lemma 4.

## C Missing Proofs from Section 5.1

## Proposition 1.

$$
\begin{aligned}
\left\|F\left(z_{k}\right)\right\|^{2}-\left\|F\left(z_{k+1}\right)\right\|^{2} & +2 \cdot\left\langle F\left(z_{k+1}\right)-F\left(z_{k}\right), F\left(z_{k+\frac{1}{2}}\right)\right\rangle \\
& +\left(\left\|F\left(z_{k+\frac{1}{2}}\right)-F\left(z_{k+1}\right)\right\|^{2}-\left\|F\left(z_{k+\frac{1}{2}}\right)-F\left(z_{k}\right)\right\|^{2}\right)=0 .
\end{aligned}
$$

Proof. Expanding the LHS of the equation in the statement we can verify that

$$
\begin{aligned}
\left\|F\left(z_{k}\right)\right\|^{2}-\left\|F\left(z_{k+1}\right)\right\|^{2} & +2 \cdot\left\langle F\left(z_{k+1}\right), F\left(z_{k+\frac{1}{2}}\right)\right\rangle-2 \cdot\left\langle F\left(z_{k}\right), F\left(z_{k+\frac{1}{2}}\right)\right\rangle \\
& +\left\|F\left(z_{k+\frac{1}{2}}\right)\right\|^{2}-2 \cdot\left\langle F\left(z_{k+1}\right), F\left(z_{k+\frac{1}{2}}\right)\right\rangle+\left\|F\left(z_{k+1}\right)\right\|^{2} \\
& -\left\|F\left(z_{k+\frac{1}{2}}\right)\right\|^{2}+2 \cdot\left\langle F\left(z_{k}\right), F\left(z_{k+\frac{1}{2}}\right)\right\rangle-\left\|F\left(z_{k}\right)\right\|^{2}=0 .
\end{aligned}
$$

## D Non-Monotonicity of Several Standard Performance Measures

We conduct numerical experiments by trying to find saddle points in constrained bilinear games using EG, and verified that the following performance measures are not monotone: the (squared) natural residual, $\left\|z_{k}-z_{k+\frac{1}{2}}\right\|^{2},\left\|z_{k}-z_{k+1}\right\|^{2}, \max _{z \in \mathcal{Z}}\left\langle F(z), z_{k}-z\right\rangle, \max _{z \in \mathcal{Z}}\left\langle F\left(z_{k}\right), z_{k}-z\right\rangle$.

All of our counterexamples are constructed by trying to find a saddle point in bilinear games of the following form:

$$
\begin{equation*}
\min _{x \in \mathcal{X}} \max _{y \in \mathcal{Y}} x^{\top} A y-b^{\top} x-c^{\top} y \tag{35}
\end{equation*}
$$

where $\mathcal{X}, \mathcal{Y} \subseteq \mathbb{R}^{2}, A$ is a $2 \times 2$ matrix and $b, c$ are 2 -dimensional column vectors. All of the instances of the bilinear game considered in this section have $\mathcal{X}, \mathcal{Y}=[0,10]^{2}$. We denote by
$\mathcal{Z}=\mathcal{X} \times \mathcal{Y}$ and by $F(x, y)=\binom{A y-b}{-A^{\top} x+c}: \mathcal{Z} \rightarrow \mathbb{R}^{n}$. We remind readers that finding a saddle point of bilinear game (35), is equivalent to solving the monotone VI with operator $F(z)$ on set $\mathcal{Z}$.

## D. 1 Non-Monotonicity of the Natural Residual and its Variants

Performance Measure: Natural Residual. Let $A=\left[\begin{array}{ll}1 & 2 \\ 1 & 1\end{array}\right], b=c=\left[\begin{array}{l}1 \\ 1\end{array}\right]$. Running the EG method on the corresponding VI problem with step-size $\eta=0.1$ starting at $z_{0}=$ $(0.3108455,0.4825575,0.4621875,0.5768655)^{T}$ has the following trajectory:

$$
\begin{aligned}
& z_{1}=(0.24923465,0.47967569,0.43497808,0.57458145)^{T}, \\
& z_{2}=(0.19396855,0.48164918,0.40193211,0.56061753)^{T} .
\end{aligned}
$$

Thus we have

$$
\begin{aligned}
& r^{\text {nat }}\left(z_{0}\right)^{2}=0.15170013184049996 \\
& r^{\text {nat }}\left(z_{1}\right)^{2}=0.13617654362050116 \\
& r^{\text {nat }}\left(z_{2}\right)^{2}=0.16125792556139756
\end{aligned}
$$

It is clear that the natural residual is not monotone.
Performance Measure: $\left\|z_{k}-z_{k+\frac{1}{2}}\right\|^{2}$. Note that the norm of the operator mapping defined in [Diakonikolas, 2020] is exactly $\frac{1}{\eta} \cdot\left\|z_{k}-z_{k+\frac{1}{2}}\right\|$. Let $A=\left[\begin{array}{ll}0.50676631 & 0.15042569 \\ 0.46897595 & 0.96748026\end{array}\right], b=c=\left[\begin{array}{l}1 \\ 1\end{array}\right]$. Running the EG method on the corresponding VI problem with step-size $\eta=0.1$ starting at $z_{0}=(2.35037432,0.00333996,1.70547279,0.71065999)^{T}$ has the following trajectory:

$$
\begin{aligned}
z_{\frac{1}{2}} & =(2.35325656,0,1.72473848,0.64633879)^{T}, \\
z_{1} & =(2.35324779,0,1.72472791,0.64605901)^{T}, \\
z_{1+\frac{1}{2}} & =(2.35612601,0,1.74398258,0.58145791)^{T} \\
z_{2} & =(2.35612201,0,1.74412844,0.5815012)^{T}, \\
z_{2+\frac{1}{2}} & =(2.35898819,0,1.76352876,0.51694333)^{T} .
\end{aligned}
$$

Thus we have

$$
\begin{aligned}
\left\|z_{0}-z_{\frac{1}{2}}\right\|^{2} & =0.00452784581555656 \\
\left\|z_{1}-z_{1+\frac{1}{2}}\right\|^{2} & =0.004552329544896258 \\
\left\|z_{2}-z_{2+\frac{1}{2}}\right\|^{2} & =0.004552306444552208
\end{aligned}
$$

It is clear that the $\left\|z_{k}-z_{k+\frac{1}{2}}\right\|^{2}$ is not monotone.

Performance Measure: $\left\|z_{k}-z_{k+1}\right\|^{2}$. Let $A=\left[\begin{array}{ll}0.50676631 & 0.15042569 \\ 0.46897595 & 0.96748026\end{array}\right], b=c=\left[\begin{array}{l}1 \\ 1\end{array}\right]$. Running the EG method on the corresponding VI problem with step-size $\eta=0.1$ starting at $z_{0}=$ $(2.37003485,0,1.84327237,0.25934775)^{T}$ has the following trajectory:

$$
\begin{aligned}
& z_{1}=(2.37267186,0,1.86351397,0.1950396)^{T}, \\
& z_{2}=(2.37524308,0,1.88388624,0.13077023)^{T} \\
& z_{3}=(2.37774149,0.00426125,1.90438549,0.06653856)^{T} .
\end{aligned}
$$

Thus we have

$$
\begin{aligned}
\left\|z_{0}-z_{1}\right\|^{2} & =0.004552214685275266 \\
\left\|z_{1}-z_{2}\right\|^{2} & =0.004552191904998012 \\
\left\|z_{2}-z_{3}\right\|^{2} & =0.004570327450598002
\end{aligned}
$$

It is clear that the $\left\|z_{k}-z_{k+1}\right\|^{2}$ is not monotone.

## D. 2 Non-Monotonicity of the Gap Functions and its Variant

Performance Measure: Gap Function and $\max _{z \in \mathcal{Z}}\left\langle F(z), z_{k}-z\right\rangle$. Let $A=$ $\left[\begin{array}{cc}-0.21025101 & 0.22360196 \\ 0.40667685 & -0.2922158\end{array}\right], b=c=\left[\begin{array}{l}0 \\ 0\end{array}\right]$. One can easily verify that $\left\langle F(z), z_{k}-z\right\rangle=$ $\left\langle F\left(z_{k}\right), z_{k}-z\right\rangle$, which further implies that $\max _{z \in \mathcal{Z}}\left\langle F(z), z_{k}-z\right\rangle=\max _{z \in \mathcal{Z}}\left\langle F\left(z_{k}\right), z_{k}-z\right\rangle=$ $\operatorname{GAP}\left(z_{k}\right)$, which implies that non-monotonicity of the gap function implies non-monotonicity of $\max _{z \in \mathcal{Z}}\left\langle F(z), z_{k}-z\right\rangle$. Running the EG method on the corresponding VI problem with step-size $\eta=0.1$ starting at $z_{0}=(0.53095379,0.29084076,0.62132986,0.49440498)$ has the following trajectory:

$$
\begin{aligned}
& z_{1}=(0.53290086,0.28009156,0.62151204,0.4981395)^{T} \\
& z_{2}=(0.5347502,0.26947398,0.62122195,0.50222691)^{T} .
\end{aligned}
$$

One can easily verify that

$$
\begin{aligned}
& \operatorname{GAP}\left(z_{0}\right)=0.6046398415472187 \\
& \operatorname{GAP}\left(z_{1}\right)=0.58462873354003214 \\
& \operatorname{GAP}\left(z_{2}\right)=0.5914026255469654
\end{aligned}
$$

It is clear that the duality gap is not monotone.

## E Optimistic Gradient Descent Ascent Algorithm

Let $\mathcal{Z} \subseteq \mathbb{R}^{n}$ be a closed convex set and $F: \mathcal{Z} \rightarrow \mathbb{R}$ be an operator. Let $z_{k}$ and $w_{k}$ be the $k$-th iterate of the Optimistic Gradient Descent Ascent algorithm (OGDA) algorithm. Let $z_{0}$, $w_{0}$ be arbitrary
point in $\mathcal{Z}$ and $\left\{z_{k}, w_{k}\right\}_{k \geq 0}$ be the iterated of the OGDA algorithm. The update rule for any $k \geq 0$ is as follows:

$$
\begin{align*}
w_{k+1} & =\Pi_{\mathcal{Z}}\left[z_{k}-\eta F\left(w_{k}\right)\right]=\arg \min _{z \in \mathcal{Z}}\left\|z-\left(z_{k}-\eta F\left(w_{k}\right)\right)\right\| \\
z_{k+1} & =\Pi_{\mathcal{Z}}\left[z_{k}-\eta F\left(w_{k+1}\right)\right]=\arg \min _{z \in \mathcal{Z}}\left\|z-\left(z_{k}-\eta F\left(w_{k+1}\right)\right)\right\| \tag{36}
\end{align*}
$$

We prove last-iterate convergence for OGDA with respect to the gap function, natural residual and tangent residual in Theorem 8 at Section E.4. The last-iterate convergence proof for OGDA is a simple extension of the proof for EG. The last-iterate convergence for the performance measures we mentioned follow from the last-iterate convergence of the following monotonically decreasing potential function:

$$
\begin{equation*}
\Phi_{k}=\left\|F\left(z_{k}\right)-F\left(w_{k}\right)\right\|^{2}+r^{\tan }\left(z_{k}\right)^{2} \tag{37}
\end{equation*}
$$

In Section E. 1 we show that OGDA enjoys last-iterate convergence with respect to the quantity $\left\|z_{k}-w_{k+1}\right\|$ [Wei et al., 2021a, Hsieh et al., 2019] and in Section E. 2 we show how to upper bound the potential function $\Phi_{k}$ by the best-iterate. In Section E. 3 we show that the potential function $\Phi_{k}$ is monotonically decreasing across iterates and finally in Section E. 4 we show how to translate the last-iterate convergence with respect to the potential function $\Phi_{k}$ to last-iterate convergence of the performance measures of interest.

## E. 1 Best-Iterate Convergence of OGDA with Constant Step Size

Best-iterate convergence guarantees for OGDA are known [Wei et al., 2021a] and can easily be derived by Hsieh et al. [2019]. We include the proof here for completeness.

Lemma 9. Let $\mathcal{Z} \subseteq \mathbb{R}^{n}$ be a closed convex set, $F: \mathcal{Z} \rightarrow \mathbb{R}$ be a monotone and L-Lipschitz operator, and $z^{*}$ be a saddle point. Let $z_{0}, w_{0} \in \mathcal{Z}$ be arbitrary starting points and $\left\{z_{k}, w_{k}\right\}_{k \geq 0}$ be the iterates of the OGDA algorithm with any step size $\eta \in\left(0, \frac{1}{2 L}\right)$. Then for all $T \geq 1$,

$$
\begin{equation*}
\sum_{k=0}^{T}\left\|z_{k}-w_{k+1}\right\|^{2} \leq \frac{1-2 \eta^{2} L^{2}}{1-4 \eta^{2} L^{2}}\left\|z_{0}-z^{*}\right\|^{2}+\frac{2 \eta^{2} L^{2}}{1-4 \eta^{2} L^{2}}\left\|w_{0}-z_{0}\right\|^{2} \tag{38}
\end{equation*}
$$

Proof of Lemma 9: In order to upper bound $\sum_{k=0}^{T}\left\|w_{k}-w_{k+1}\right\|^{2}$, we first relate the quantity $\left\|w_{k}-w_{k+1}\right\|^{2}$ to the weighted sum of $\left\{\left\|z_{t}-w_{t+1}\right\|^{2}\right\}_{0 \leq t \leq k}$.

Lemma 10. For all $k \geq 0$,

$$
\begin{equation*}
\left\|w_{k}-w_{k+1}\right\|^{2} \leq 2\left(2 \eta^{2} L^{2}\right)^{k}\left\|w_{0}-z_{0}\right\|^{2}+\sum_{t=0}^{k} 2\left(2 \eta^{2} L^{2}\right)^{t}\left\|z_{k-t}-w_{k+1-t}\right\|^{2} . \tag{39}
\end{equation*}
$$

Moreover, for all $T \geq 0$,

$$
\begin{equation*}
\sum_{k=0}^{T}\left\|w_{k}-w_{k+1}\right\|^{2} \leq \frac{2}{1-2 \eta^{2} L^{2}}\left(\left\|w_{0}-z_{0}\right\|^{2}+\sum_{k=0}^{T}\left\|z_{k}-w_{k+1}\right\|^{2}\right) \tag{40}
\end{equation*}
$$

Proof. We first prove Equation (39) by induction. Note that for all $k \geq 0$, we have

$$
\begin{align*}
\left\|w_{k}-w_{k+1}\right\|^{2} & =\left\|w_{k}-z_{k}+z_{k}-w_{k+1}\right\|^{2} \\
& \leq 2\left\|w_{k}-z_{k}\right\|^{2}+2\left\|z_{k}-w_{k+1}\right\|^{2} . \tag{41}
\end{align*}
$$

The inequality follows from the fact that $(a+b)^{2} \leq 2 a^{2}+2 b^{2}$. Thus Equation (39) holds for the base case $k=0$. For the sake of induction, we assume that Equation (39) holds for some $k-1 \geq 0$. Using the update rule of OGDA, the non-expansiveness of the projection operator, and the $L$ Lipschitzness of $F$, for all $k \geq 1$ we have

$$
\begin{equation*}
\left\|w_{k}-z_{k}\right\|^{2} \leq \eta^{2}\left\|F\left(w_{k-1}\right)-F\left(w_{k}\right)\right\|^{2} \leq \eta^{2} L^{2}\left\|w_{k-1}-w_{k}\right\|^{2} . \tag{42}
\end{equation*}
$$

Combining Equation (41), Equation (42), and the induction assumption, we have

$$
\begin{aligned}
\left\|w_{k}-w_{k+1}\right\|^{2} & \leq 2\left\|w_{k}-z_{k}\right\|^{2}+2\left\|z_{k}-w_{k+1}\right\|^{2} \\
& \leq 2 \eta^{2} L^{2}\left\|w_{k-1}-w_{k}\right\|^{2}+2\left\|z_{k}-w_{k+1}\right\|^{2} \\
& \leq 2 \eta^{2} L^{2}\left(2\left(2 \eta^{2} L^{2}\right)^{k-1}\left\|w_{0}-z_{0}\right\|^{2}+\sum_{t=0}^{k-1} 2\left(2 \eta^{2} L^{2}\right)^{t}\left\|z_{k-1-t}-w_{k-t}\right\|^{2}\right)+2\left\|z_{k}-w_{k+1}\right\|^{2} \\
& =2\left(2 \eta^{2} L^{2}\right)^{k}\left\|w_{0}-z_{0}\right\|^{2}+\sum_{t=1}^{k} 2\left(2 \eta^{2} L^{2}\right)^{t}\left\|z_{k-t}-w_{k+1-t}\right\|^{2}+2\left\|z_{k}-w_{k+1}\right\|^{2} \\
& =2\left(2 \eta^{2} L^{2}\right)^{k}\left\|w_{0}-z_{0}\right\|^{2}+\sum_{t=0}^{k} 2\left(2 \eta^{2} L^{2}\right)^{t}\left\|z_{k-t}-w_{k+1-t}\right\|^{2} .
\end{aligned}
$$

This completes the proof of Equation (39).
Summing Equation (39) with $k=0,1, \cdots, T$, we have

$$
\begin{aligned}
\sum_{k=0}^{T}\left\|w_{k}-w_{k+1}\right\|^{2} & \leq \sum_{k=0}^{T} 2\left(2 \eta^{2} L^{2}\right)^{k}\left\|w_{0}-z_{0}\right\|^{2}+\sum_{k=0}^{T} \sum_{t=0}^{k} 2\left(2 \eta^{2} L^{2}\right)^{t}\left\|z_{k-t}-w_{k+1-t}\right\|^{2} \\
& =\sum_{k=0}^{T} 2\left(2 \eta^{2} L^{2}\right)^{k}\left\|w_{0}-z_{0}\right\|^{2}+\sum_{k=0}^{T}\left(\sum_{t=0}^{T-k} 2\left(2 \eta^{2} L^{2}\right)^{t}\right) \cdot\left\|z_{k}-w_{k+1}\right\|^{2} \\
& \leq \frac{2}{1-2 \eta^{2} L^{2}}\left(\left\|w_{0}-z_{0}\right\|^{2}+\sum_{k=0}^{T}\left\|z_{k}-w_{k+1}\right\|^{2}\right)
\end{aligned}
$$

This completes the proof of Equation (40).
Back to the proof of Lemma 9. For all $k \geq 0$, we have

$$
\begin{align*}
\left\|z_{k+1}-z^{*}\right\|^{2} & =\left\|z_{k+1}-z_{k}+z_{k}-z^{*}\right\|^{2} \\
& =\left\|z_{k}-z^{*}\right\|^{2}+\left\|z_{k+1}-z_{k}\right\|^{2}+2\left\langle z_{k+1}-z_{k}, z_{k}-z^{*}\right\rangle \\
& =\left\|z_{k}-z^{*}\right\|^{2}-\left\|z_{k+1}-z_{k}\right\|^{2}+2\left\langle z_{k+1}-z_{k}, z_{k+1}-z^{*}\right\rangle \\
& \leq\left\|z_{k}-z^{*}\right\|^{2}-\left\|z_{k+1}-z_{k}\right\|^{2}-2 \eta\left\langle F\left(w_{k+1}\right), z_{k+1}-z^{*}\right\rangle \tag{43}
\end{align*}
$$

The last inequality follows from $\left\langle z_{k+1}-z_{k}+\eta F\left(w_{k+1}\right), z_{k+1}-z^{*}\right\rangle \leq 0$ as $z_{k+1}=$ $\Pi_{\mathcal{Z}}\left[z_{k}-\eta F\left(w_{k+1}\right)\right]$.

Similarly, for all $k \geq 0$, we have

$$
\begin{align*}
\left\|z_{k+1}-w_{k+1}\right\|^{2} & =\left\|z_{k+1}-z_{k}+z_{k}-w_{k+1}\right\|^{2} \\
& =\left\|z_{k+1}-z_{k}\right\|^{2}+\left\|z_{k}-w_{k+1}\right\|^{2}+2\left\langle z_{k}-w_{k+1}, z_{k+1}-z_{k}\right\rangle \\
& =\left\|z_{k+1}-z_{k}\right\|^{2}-\left\|z_{k}-w_{k+1}\right\|^{2}+2\left\langle z_{k}-w_{k+1}, z_{k+1}-w_{k+1}\right\rangle \\
& \leq\left\|z_{k+1}-z_{k}\right\|^{2}-\left\|z_{k}-w_{k+1}\right\|^{2}+2 \eta\left\langle F\left(w_{k}\right), z_{k+1}-w_{k+1}\right\rangle . \tag{44}
\end{align*}
$$

The last inequality follows from $\left\langle z_{k}-\eta F\left(w_{k}\right)-w_{k+1}, z_{k+1}-w_{k+1}\right\rangle \leq 0$ as $w_{k+1}=$ $\Pi_{\mathcal{Z}}\left[z_{k}-\eta F\left(w_{k}\right)\right]$.

We can further simplify Equation (43) using Fact 1:

$$
\begin{align*}
\left\|z_{k+1}-z^{*}\right\|^{2} & \leq\left\|z_{k}-z^{*}\right\|^{2}-\left\|z_{k+1}-z_{k}\right\|^{2}-2 \eta\left\langle F\left(w_{k+1}\right), z_{k+1}-z^{*}\right\rangle \\
& =\left\|z_{k}-z^{*}\right\|^{2}-\left\|z_{k+1}-z_{k}\right\|^{2}-2 \eta\left\langle F\left(w_{k+1}\right), z_{k+1}-w_{k+1}\right\rangle+2 \eta\left\langle F\left(w_{k+1}\right), z^{*}-w_{k+1}\right\rangle \\
& \leq\left\|z_{k}-z^{*}\right\|^{2}-\left\|z_{k+1}-z_{k}\right\|^{2}-2 \eta\left\langle F\left(w_{k+1}\right), z_{k+1}-w_{k+1}\right\rangle . \tag{45}
\end{align*}
$$

Summing Equation (44) and Equation (45), we get

$$
\begin{align*}
\left\|z_{k+1}-z^{*}\right\|^{2} & \leq\left\|z_{k}-z^{*}\right\|^{2}-\left\|z_{k}-w_{k+1}\right\|^{2}-\left\|z_{k+1}-w_{k+1}\right\|^{2}+2 \eta\left\langle F\left(w_{k}\right)-F\left(w_{k+1}\right), z_{k+1}-w_{k+1}\right\rangle \\
& \leq\left\|z_{k}-z^{*}\right\|^{2}-\left\|z_{k}-w_{k+1}\right\|^{2}-\left\|z_{k+1}-w_{k+1}\right\|^{2}+2 \eta\left\|F\left(w_{k}\right)-F\left(w_{k+1}\right)\right\|\left\|z_{k+1}-w_{k+1}\right\| \\
& \leq\left\|z_{k}-z^{*}\right\|^{2}-\left\|z_{k}-w_{k+1}\right\|^{2}-\left\|z_{k+1}-w_{k+1}\right\|^{2}+2 \eta L\left\|w_{k}-w_{k+1}\right\|\left\|z_{k+1}-w_{k+1}\right\| \\
& \leq\left\|z_{k}-z^{*}\right\|^{2}-\left\|z_{k}-w_{k+1}\right\|^{2}+\eta^{2} L^{2}\left\|w_{k}-w_{k+1}\right\|^{2} \tag{46}
\end{align*}
$$

where we use Cauchy-Schwarz inequality in the second inequality and $L$-Lipschitzness of $F(\cdot)$ in the third inequality. In the last inequality, we optimize the quadratic function in $\left\|z_{k+1}-w_{k+1}\right\|$.

Summing Equation (46) for $k=0,1, \cdots, T$ and using Lemma 10, we get

$$
\begin{align*}
\left\|z_{T+1}-z^{*}\right\|^{2} & \leq\left\|z_{0}-z^{*}\right\|^{2}-\sum_{k=0}^{T}\left\|z_{k}-w_{k+1}\right\|^{2}+\eta^{2} L^{2} \sum_{k=0}^{T}\left\|w_{k}-w_{k+1}\right\|^{2} \\
& \leq\left\|z_{0}-z^{*}\right\|^{2}-\sum_{k=0}^{T}\left\|z_{k}-w_{k+1}\right\|^{2}+\frac{2 \eta^{2} L^{2}}{1-2 \eta^{2} L^{2}}\left(\left\|w_{0}-z_{0}\right\|^{2}+\sum_{k=0}^{T}\left\|z_{k}-w_{k+1}\right\|^{2}\right)  \tag{Lemma10}\\
& =\left\|z_{0}-z^{*}\right\|^{2}-\frac{1-4 \eta^{2} L^{2}}{1-2 \eta^{2} L^{2}} \sum_{k=0}^{T}\left\|z_{k}-w_{k+1}\right\|^{2}+\frac{2 \eta^{2} L^{2}}{1-2 \eta^{2} L^{2}}\left\|w_{0}-z_{0}\right\|^{2}
\end{align*}
$$

Since $\eta^{2} L^{2}<\frac{1}{4}$, we complete the proof by rearranging the above inequality.

## E. 2 Best-Iterate of $\Phi_{k}$

In this section, we use Lemma 9 to show that there exists $t^{*} \in[T]$ such that $\Phi_{t^{*}}=O\left(\frac{1}{T}\right)$.
Lemma 11. Let $\mathcal{Z} \subseteq \mathbb{R}^{n}$ be a closed convex set, $F: \mathcal{Z} \rightarrow \mathbb{R}$ be a monotone and L-Lipschitz operator, and $z^{*}$ be a saddle point. Let $z_{0}, w_{0} \in \mathcal{Z}$ be arbitrary starting point and $\left\{z_{k}, w_{k}\right\}_{k \geq 0}$ be the iterates of the OGDA algorithm with any step size $\eta \in\left(0, \frac{1}{2 L}\right)$. Then for all $T \geq 1$,

$$
\sum_{k=1}^{T}\left(\left\|\eta F\left(z_{k}\right)-\eta F\left(w_{k}\right)\right\|^{2}+\eta^{2} r^{t a n}\left(z_{k}\right)^{2}\right) \leq \frac{4+6 \eta^{4} L^{4}}{1-4 \eta^{2} L^{2}}\left\|z_{0}-z^{*}\right\|^{2}+\frac{16 \eta^{2} L^{2}+6 \eta^{4} L^{4}}{1-4 \eta^{2} L^{2}}\left\|w_{0}-z_{0}\right\|^{2}
$$

Moreover, when $w_{0}=z_{0}$

$$
\sum_{k=1}^{T}\left(\left\|\eta F\left(z_{k}\right)-\eta F\left(w_{k}\right)\right\|^{2}+\eta^{2} r^{t a n}\left(z_{k}\right)^{2}\right) \leq \frac{4+6 \eta^{4} L^{4}}{1-4 \eta^{2} L^{2}}\left\|z_{0}-z^{*}\right\|^{2}
$$

Proof of Lemma 11: For all $k \geq 1$, we have

$$
\begin{aligned}
\left\|\eta F\left(z_{k}\right)-\eta F\left(w_{k}\right)\right\|^{2} & \leq \eta^{2} L^{2}\left\|z_{k}-w_{k}\right\|^{2} \\
& \leq \eta^{4} L^{4}\left\|w_{k-1}-w_{k}\right\|^{2} .
\end{aligned}
$$

Using Lemma 8 with the fact that $z_{k}=\Pi_{\mathcal{Z}}\left[z_{k-1}-\eta F\left(w_{k}\right)\right]$, we have for all $k \geq 1$,

$$
\begin{align*}
& \eta^{2} r^{\tan }\left(z_{k}\right)^{2} \leq\left\|z_{k-1}-z_{k}+\eta F\left(z_{k}\right)-\eta F\left(w_{k}\right)\right\|^{2} \\
& \leq 2\left\|z_{k-1}-z_{k}\right\|^{2}+2 \eta^{2}\left\|F\left(z_{k}\right)-F\left(w_{k}\right)\right\|^{2} \\
& \leq 2\left\|z_{k-1}-w_{k}+w_{k}-z_{k}\right\|^{2}+2 \eta^{2} L^{2}\left\|w_{k}-z_{k}\right\|^{2} \quad \quad \text { (L-Lipschitzness of } F \text { ) } \\
& \leq 4\left\|z_{k-1}-w_{k}\right\|^{2}+\left(4+2 \eta^{2} L^{2}\right)\left\|w_{k}-z_{k}\right\|^{2} \\
& \leq 4\left\|z_{k-1}-w_{k}\right\|^{2}+\left(4+2 \eta^{2} L^{2}\right) \eta^{2} L^{2}\left\|w_{k-1}-w_{k}\right\|^{2} .  \tag{42}\\
& \text { (Equation (42)) }
\end{align*}
$$

Summing the above inequalities with $k=1, \cdots, T$ and using Lemma 9 and Lemma 10 , we
have

$$
\begin{aligned}
& \sum_{k=1}^{T}\left(\left\|\eta F\left(z_{k}\right)-\eta F\left(w_{k}\right)\right\|^{2}+\eta^{2} r^{t a n}\left(z_{k}\right)^{2}\right) \\
& \leq 4 \sum_{k=0}^{T-1}\left\|z_{k}-w_{k+1}\right\|^{2}+\left(4+3 \eta^{2} L^{2}\right) \eta^{2} L^{2} \sum_{k=0}^{T-1}\left\|w_{k}-w_{k+1}\right\|^{2} \\
& \leq \frac{2\left(4+3 \eta^{2} L^{2}\right) \eta^{2} L^{2}}{1-2 \eta^{2} L^{2}}\left\|w_{0}-z_{0}\right\|^{2}+\left(4+\frac{2\left(4+3 \eta^{2} L^{2}\right) \eta^{2} L^{2}}{1-2 \eta^{2} L^{2}}\right) \sum_{k=0}^{T-1}\left\|z_{k}-w_{k+1}\right\|^{2} \\
& \leq \frac{2\left(4+3 \eta^{2} L^{2}\right) \eta^{2} L^{2}}{1-2 \eta^{2} L^{2}}\left\|w_{0}-z_{0}\right\|^{2}+\left(\frac{8 \eta^{2} L^{2}}{1-4 \eta^{2} L^{2}}+\frac{4\left(4+3 \eta^{2} L^{2}\right) \eta^{4} L^{4}}{\left(1-2 \eta^{2} L^{2}\right) \cdot\left(1-4 \eta^{2} L^{2}\right)}\right)\left\|w_{0}-z_{0}\right\|^{2} \\
& \quad+\left(\frac{4-8 \eta^{2} L^{2}}{1-4 \eta^{2} L^{2}}+\frac{2\left(4+3 \eta^{2} L^{2}\right) \eta^{2} L^{2}}{1-4 \eta^{2} L^{2}}\right)\left\|z_{0}-z^{*}\right\|^{2} \\
& =\frac{16 \eta^{2} L^{2}+6 \eta^{4} L^{4}}{1-4 \eta^{2} L^{2}}\left\|w_{0}-z_{0}\right\|^{2}+\frac{4+6 \eta^{4} L^{4}}{1-4 \eta^{2} L^{2}}\left\|z_{0}-z^{*}\right\|^{2},
\end{aligned}
$$

which concludes the proof.
Corollary 2. Let $\mathcal{Z} \subseteq \mathbb{R}^{n}$ be a closed convex set, $F: \mathcal{Z} \rightarrow \mathbb{R}$ be a monotone and L-Lipschitz operator, and $z^{*}$ be a saddle point. Let $z_{0}, w_{0} \in \mathcal{Z}$ be arbitrary starting point and $\left\{z_{k}, w_{k}\right\}_{k \geq 0}$ be the iterates of the OGDA algorithm with any step size $\eta \in\left(0, \frac{1}{2 L}\right)$. Then for all $T \geq 1$, there exists $t^{*} \in[T]$ such that

$$
\left\|\eta F\left(z_{t^{*}}\right)-\eta F\left(w_{t^{*}}\right)\right\|^{2}+\eta^{2} r^{\tan }\left(z_{t^{*}}\right)^{2} \leq \frac{1}{T} \frac{4+6 \eta^{4} L^{4}}{1-4 \eta^{2} L^{2}}\left\|z_{0}-z^{*}\right\|^{2}+\frac{1}{T} \frac{16 \eta^{2} L^{2}+6 \eta^{4} L^{4}}{1-4 \eta^{2} L^{2}}\left\|w_{0}-z_{0}\right\|^{2}
$$

Moreover, when $w_{0}=z_{0}$

$$
\left\|\eta F\left(z_{t^{*}}\right)-\eta F\left(w_{t^{*}}\right)\right\|^{2}+\eta^{2} r^{\tan }\left(z_{t^{*}}\right)^{2} \leq \frac{1}{T} \frac{4+6 \eta^{4} L^{4}}{1-4 \eta^{2} L^{2}}\left\|z_{0}-z^{*}\right\|^{2}
$$

## E. 3 Monotonicity of the Potential

In this section we show that the potential function $\Phi_{k}$ is monotonically decreasing across iterates of OGDA. We only include the simplified proof discovered using a degree 2 SOS program. The original proof is based on a higher degree SOS program and can be found in an earlier version of this paper [Cai et al., 2022] and at this link.

Theorem 7. Let $\mathcal{Z} \subseteq \mathbb{R}^{n}$ be a closed convex set and $F: \mathcal{Z} \rightarrow \mathbb{R}$ be a monotone and L-Lipschitz operator. Then for any $z_{k}$, $w_{k} \in \mathcal{Z}$, the OGDA algorithm with any step size $\eta \in\left(0, \frac{1}{2 L}\right)$ produces $w_{k+1}, z_{k+1} \in \mathcal{Z}$ that satisfy $\left\|F\left(z_{k}\right)-F\left(w_{k}\right)\right\|^{2}+r^{\text {tan }}\left(z_{k}\right)^{2} \geq\left\|F\left(z_{k+1}\right)-F\left(w_{k+1}\right)\right\|^{2}+r^{\text {tan }}\left(z_{k+1}\right)^{2}$.

Proof. Let $c_{k}=\Pi_{N_{\mathcal{Z}}\left(z_{k}\right)}\left(-F\left(z_{k}\right)\right)$ and $c_{k+1}=\Pi_{N_{\mathcal{Z}}\left(z_{k+1}\right)}\left(-F\left(z_{k+1}\right)\right)$. Lemma 6 implies that

$$
\begin{align*}
& \eta^{2} r^{\tan }\left(z_{k}\right)^{2}+\eta^{2}\left\|F\left(z_{k}\right)-F\left(w_{k}\right)\right\|^{2}-\left(\eta^{2} r^{\tan }\left(z_{k+1}\right)^{2}+\left\|F\left(z_{k+1}\right)-F\left(w_{k+1}\right)\right\|^{2}\right) \\
& =\left\|\eta F\left(z_{k}\right)+\eta c_{k}\right\|^{2}+\eta^{2}\left\|F\left(z_{k}\right)-F\left(w_{k}\right)\right\|^{2} \\
& \quad-\left(\left\|\eta F\left(z_{k+1}\right)+\eta c_{k+1}\right\|^{2}+\left\|F\left(z_{k+1}\right)-F\left(w_{k+1}\right)\right\|^{2}\right) \tag{47}
\end{align*}
$$

Since $F$ is monotone and $L$-Lipschitz, and $\eta \in\left(0, \frac{1}{2 L}\right)$, we have

$$
\begin{align*}
(-2) \cdot\left(\left\langle\eta F\left(z_{k+1}\right)-\eta F\left(z_{k}\right), z_{k+1}-z_{k}\right\rangle\right) & \leq 0  \tag{48}\\
(-2) \cdot\left(\frac{1}{4}\left\|z_{k+1}-w_{k+1}\right\|^{2}-\left\|\eta F\left(z_{k+1}\right)-\eta F\left(w_{k+1}\right)\right\|^{2}\right) & \leq 0 . \tag{49}
\end{align*}
$$

Since $w_{k+1}=\Pi_{\mathcal{Z}}\left[z_{k}-\eta F\left(w_{k}\right)\right]$ and $z_{k+1}=\Pi_{\mathcal{Z}}\left[z_{k}-\eta F\left(w_{k+1}\right)\right]$, we have that $z_{k}-\eta F\left(w_{k}\right)-$ $w_{k+1} \in N\left(w_{k+1}\right)$ and $z_{k}-\eta F\left(w_{k+1}\right)-z_{k+1} \in N\left(z_{k+1}\right)$. Thus we have

$$
\begin{array}{r}
(-1) \cdot\left\langle z_{k}-\eta F\left(w_{k}\right)-w_{k+1}, w_{k+1}-z_{k+1}\right\rangle \leq 0 \\
(-2) \cdot\left\langle z_{k}-\eta F\left(w_{k+1}\right)-z_{k+1}, z_{k+1}-z_{k}\right\rangle \leq 0 \tag{51}
\end{array}
$$

Since $c\left(z_{k}\right) \in N\left(z_{k}\right)$, we have that

$$
\begin{align*}
(-1) \cdot\left\langle\eta c\left(z_{k}\right), z_{k}-w_{k+1}\right\rangle & \leq 0  \tag{52}\\
(-1) \cdot\left\langle\eta c\left(z_{k}\right), z_{k}-z_{k+1}\right\rangle & \leq 0 . \tag{53}
\end{align*}
$$

According to Lemma 6 and the fact that $z_{k}-\eta F\left(w_{k+1}\right)-z_{k+1} \in N\left(z_{k+1}\right), c_{k+1} \in$ $\Pi_{N\left(z_{k+1}\right)}\left(-F\left(z_{k+1}\right)\right)$ we have

$$
\begin{array}{r}
(-2) \cdot\left\langle\eta c\left(z_{k+1}\right)+\eta F\left(z_{k+1}\right), z_{k}-\eta F\left(w_{k+1}\right)-z_{k+1}\right\rangle \leq 0, \\
(-2) \cdot\left\langle\eta c\left(z_{k+1}\right)+\eta F\left(z_{k+1}\right),-c\left(z_{k+1}\right)\right\rangle=0, . \tag{55}
\end{array}
$$

MATLAB code for the verification of the following identity can be found at this link.

Expression (47) + LHS of Inequality (48) + LHS of Inequality (49) + LHS of Inequality (50)

+ LHS of Inequality (51) + LHS of Inequality (52) + LHS of Inequality (53)
+ LHS of Inequality (55) + LHS of Inequality (54)
$=\left\|\frac{w_{k+1}-z_{k+1}}{2}+\eta F\left(w_{k}\right)-\eta F\left(z_{k}\right)\right\|^{2}$
$+\left\|\eta F\left(z_{k}\right)+\eta c\left(z_{k}\right)-z_{k}+\frac{w_{k+1}+z_{k+1}}{2}\right\|^{2}$
$+\left\|z_{k}-\eta F\left(w_{k+1}\right)-z_{k+1}-\eta c\left(z_{k+1}\right)\right\|^{2}$
$\geq 0$.
Thus, $\left\|F\left(z_{k}\right)-F\left(w_{k}\right)\right\|^{2}+r^{\tan }\left(z_{k}\right)^{2} \geq\left\|F\left(z_{k+1}\right)-F\left(w_{k+1}\right)\right\|^{2}+r^{\tan }\left(z_{k+1}\right)^{2}$.


## E. 4 Combining Everything

In this section, we combine the results of the previous sections and show that $\Phi_{T}=O\left(\frac{1}{T}\right)$ and we show the last-iterate convergence rate for performance measures of iterest.

Lemma 12. Let $\mathcal{Z} \subseteq \mathbb{R}^{n}$ be a closed convex set and $F: \mathcal{Z} \rightarrow \mathbb{R}$ be a monotone and L-Lipschitz operator. Let $z_{0}, w_{0} \in \mathcal{Z}$ be arbitrary starting point and $\left\{z_{k}, w_{k}\right\}_{k \geq 0}$ be the iterates of the OGDA algorithm with any step size $\eta \in\left(0, \frac{1}{2 L}\right)$. Then for any $k \geq 0$,

$$
r_{(F, \mathcal{Z})}^{\tan }\left(w_{k+1}\right) \leq \sqrt{2}(2+\eta L) \sqrt{r_{(F, \mathcal{Z})}^{t a n}\left(z_{k}\right)^{2}+\left\|F\left(w_{k}\right)-F\left(z_{k}\right)\right\|^{2}}
$$

Proof. Since $w_{k+1}=\Pi_{\mathcal{Z}}\left[z_{k}-F\left(w_{k}\right)\right]$, by using Lemma 8 we have

$$
\begin{aligned}
r_{(F, \mathcal{Z})}^{\tan }\left(w_{k+1}\right) & \leq\left\|\frac{z_{k}-w_{k+1}}{\eta}+F\left(w_{k+1}\right)-F\left(w_{k}\right)\right\| \\
& \leq\left\|\frac{z_{k}-w_{k+1}}{\eta}\right\|+\left\|F\left(w_{k}\right)-F\left(z_{k}\right)\right\|+\left\|F\left(z_{k}\right)-F\left(w_{k+1}\right)\right\| \\
& \left.\leq \frac{1+\eta L}{\eta}\left\|z_{k}-w_{k+1}\right\|+\left\|F\left(w_{k}\right)-F\left(z_{k}\right)\right\| . \quad \quad \quad \text { (L-Lipschitzness of } F\right)
\end{aligned}
$$

Using Lemma 1 and the non-expansiveness of the projection mapping, we have

$$
\begin{aligned}
\left\|z_{k}-w_{k+1}\right\| & \leq\left\|z_{k}-\Pi_{\mathcal{Z}}\left[z_{k}-\eta F\left(z_{k}\right)\right]\right\|+\left\|\Pi_{\mathcal{Z}}\left[z_{k}-\eta F\left(z_{k}\right)\right]-w_{k+1}\right\| \\
& =r_{(\eta F, \mathcal{Z})}^{\text {nat }}\left(z_{k}\right)+\left\|\Pi_{\mathcal{Z}}\left[z_{k}-\eta F\left(z_{k}\right)\right]-\Pi_{\mathcal{Z}}\left[z_{k}-\eta F\left(w_{k}\right)\right]\right\| \\
& \leq r_{(\eta F, \mathcal{Z})}^{\text {tan }}\left(z_{k}\right)+\eta\left\|F\left(z_{k}\right)-F\left(w_{k}\right)\right\| \\
& =\eta_{(F, \mathcal{Z})}^{t a n}\left(z_{k}\right)+\eta\left\|F\left(z_{k}\right)-F\left(w_{k}\right)\right\| .
\end{aligned}
$$

Combing the above two inequalities, we have

$$
\begin{aligned}
r_{(F, \mathcal{Z})}^{\tan }\left(w_{k+1}\right) & \leq(1+\eta L) r_{(F, \mathcal{Z})}^{\tan }\left(z_{k}\right)+(2+\eta L)\left\|F\left(w_{k}\right)-F\left(z_{k}\right)\right\| \\
& \leq \sqrt{2}(2+\eta L) \sqrt{r_{(F, \mathcal{Z})}^{\tan }\left(z_{k}\right)^{2}+\left\|F\left(w_{k}\right)-F\left(z_{k}\right)\right\|^{2}} . \quad\left(a+b \leq \sqrt{2} \sqrt{a^{2}+b^{2}}\right)
\end{aligned}
$$

Combining Corollary 2, Theorem 7, Lemma 12, Lemma 1 and Lemma 2 we get $\mathcal{O}\left(\frac{1}{\sqrt{T}}\right)$ lastiterate convergence in terms of the tangent residual, natural residual and gap function for both $z_{T}$ and $w_{T+1}$. The result is formally stated in Theorem 8.

Theorem 8. Let $\mathcal{Z} \subseteq \mathbb{R}^{n}$ be a closed convex set and $F: \mathcal{Z} \rightarrow \mathbb{R}$ be a monotone and L-Lipschitz operator. Let $z_{0}, w_{0} \in \mathcal{Z}$ be arbitrary starting point and $\left\{z_{k}, w_{k}\right\}_{k \geq 0}$ be the iterates of the OGDA algorithm with any step size $\eta \in\left(0, \frac{1}{2 L}\right)$. Let $D_{0}:=\sqrt{\left(4+6 \eta^{4} L^{4}\right)\left\|z_{0}-z^{*}\right\|^{2}+\left(16 \eta^{2} L^{2}+6 \eta^{4} L^{4}\right)\left\|w_{0}-z_{0}\right\|^{2}}=$ $O\left(\max \left\{\left\|z_{0}-z^{*}\right\|,\left\|w_{0}-z_{0}\right\|\right\}\right)$. Then for any $T \geq 1$,

- $\operatorname{GAP}_{\mathcal{Z}, F, D}\left(z_{T}\right) \leq \frac{1}{\sqrt{T}} \cdot \frac{D D_{0}}{\eta \sqrt{1-4 \cdot(\eta L)^{2}}}$.
- $r_{\mathcal{Z}, F, D}^{n a t}\left(z_{T}\right) \leq r_{\mathcal{Z}, F, D}^{\tan }\left(z_{T}\right) \leq \frac{1}{\sqrt{T}} \cdot \frac{D_{0}}{\eta \cdot \sqrt{\left.1-4 \cdot(\eta L)^{2}\right)}}$.
- $\operatorname{GAP}_{\mathcal{Z}, F, D}\left(w_{T+1}\right) \leq \frac{1}{\sqrt{T}} \cdot \frac{\sqrt{2}(2+\eta L) \cdot D \cdot D_{0}}{\eta \cdot \sqrt{1-4 \cdot(\eta L)^{2}}}$.
- $r_{\mathcal{Z}, F, D}^{n a t}\left(w_{T+1}\right) \leq r_{\mathcal{Z}, F, D}^{\tan }\left(w_{T+1}\right) \leq \frac{1}{\sqrt{T}} \cdot \frac{\sqrt{2}(2+\eta L) D_{0}}{\eta \cdot \sqrt{1-4 \cdot(\eta L)^{2}}}$.


## F Agnostic to Lemma 6 Proof for Monotonicity of Tangent Residual of EG

Let $a=\max _{a \in \hat{N}_{\mathcal{Z}}(z),}\langle a, F(z)$. By Definition 3, a natural formulation of the squared tangent residual $\langle F(z), a\rangle \leq 0$
is $r^{\text {tan }}(z)^{2}=\|F(z)\|^{2}-\langle a, F(z)\rangle^{2}$, which is a degree-4 formulation of the tangent residual with respect to our $\{a, F(z)\}$. In this section, we show how to prove monotonicity of tangent residual of EG with arbitrary convex constraints, while being agnostic to the degree two formulation of tangent residual as shown in Lemma 6 with the use of a higher-degree SOS program.

Reducing the Number of Constraints. Our reasoning behind reducing the number of constraints follows similar to the corresponding paragraph in Section 5.2 with minor modifications that we list here for completeness. Suppose we are not given the description of $\mathcal{Z}$, and we only observe one iteration of the EG algorithm. In other words, we know $z_{k}, z_{k+\frac{1}{2}}$, and $z_{k+1}$, as well as $F\left(z_{k}\right), F\left(z_{k+\frac{1}{2}}\right)$, and $F\left(z_{k+1}\right)$. To compute the squared tangent residual at $z_{k}$, let us also assume that the unit vector $-a_{k} \in \widehat{N}\left(z_{k}\right)$ satisfies $r_{(F, \mathcal{Z})}^{\tan }\left(z_{k}\right)^{2}=\left\|F\left(z_{k}\right)\right\|^{2}-\left\langle F\left(z_{k}\right),-a_{k}\right\rangle^{2}$. From this limited information, what can we learn about $\mathcal{Z}$ ? We can conclude that $\mathcal{Z}$ must lie in the intersection of the following halfspaces: (a) $\left\langle a_{k}, z\right\rangle \geq b_{k}$, where $b_{k}=\left\langle a_{k}, z_{k}\right\rangle$. This is true because $-a_{k} \in \widehat{N}\left(z_{k}\right)$. (b) $\left\langle a_{k+\frac{1}{2}}, z\right\rangle \geq b_{k+\frac{1}{2}}$, where $a_{k+\frac{1}{2}}=\frac{z_{k+\frac{1}{2}}-z_{k}+\eta F\left(z_{k}\right)}{\left\|z_{k+\frac{1}{2}}-z_{k}+\eta F\left(z_{k}\right)\right\|}$ and $b_{k+\frac{1}{2}}=\left\langle a_{k+\frac{1}{2}}, z_{k+\frac{1}{2}}\right\rangle$. This is true because $z_{k+\frac{1}{2}}=\Pi_{\mathcal{Z}}\left(z_{k}-\eta F\left(z_{k}\right)\right)$, so $\left\langle z_{k+\frac{1}{2}}-z_{k}+\eta F\left(z_{k}\right), z-z_{k+\frac{1}{2}}\right\rangle \geq 0$ for all $z \in \mathcal{Z}$. (c) $\left\langle a_{k+1}, z\right\rangle \geq b_{k+1}$, where $a_{k+1}=\frac{z_{k+1}-z_{k}+\eta F\left(z_{k+\frac{1}{2}}\right)}{\left\|z_{k+1}-z_{k}+\eta F\left(z_{k+\frac{1}{2}}\right)\right\|}$ and $b_{k+1}=\left\langle a_{k+1}, z_{k+1}\right\rangle$. This is true because $z_{k+1}=\Pi_{\mathcal{Z}}\left(z_{k}-\eta F\left(z_{k+\frac{1}{2}}\right)\right)$, so $\left\langle z_{k+1}-z_{k}+\eta F\left(z_{k+\frac{1}{2}}\right), z-z_{k+1}\right\rangle \geq 0$ for all $z \in \mathcal{Z}$.

The "hardest instance" of $\mathcal{Z}$ that is consistent with our knowledge of $z_{k}, z_{k+\frac{1}{2}}$, and $z_{k+1}$ is when $\mathcal{Z}$ is exactly the intersection of these three halfspaces. In such case, the squared tangent residual of $z_{k+1}$ is $\left\|F\left(z_{k+1}\right)\right\|^{2}-\left\langle F\left(z_{k+1}\right), a_{k+1}\right\rangle^{2} \cdot \mathbb{1}\left[\left\langle F\left(z_{k+1}\right), a_{k+1}\right\rangle \geq 0\right]$, and it is an upper bound of $r_{(F, \mathcal{Z})}^{\tan }\left(z_{k+1}\right)^{2}$ for any other consistent $\mathcal{Z}$. Our goal is to prove the tangent residual is non-increasing even in the "hardest case", that is, to prove the non-negativity of

$$
\begin{equation*}
\left\|F\left(z_{k}\right)\right\|^{2}-\left\langle F\left(z_{k}\right), a_{k}\right\rangle^{2}-\left(\left\|F\left(z_{k+1}\right)\right\|^{2}-\left\langle F\left(z_{k+1}\right), a_{k+1}\right\rangle^{2} \cdot \mathbb{1}\left[\left\langle F\left(z_{k+1}\right), a_{k+1}\right\rangle \geq 0\right]\right) \tag{59}
\end{equation*}
$$

Low-dimensionality of an EG Update. As there are only three hyperplanes $\left\langle a_{i}, z\right\rangle \geq b_{i}$ for $i \in\left\{k, k+\frac{1}{2}, k+1\right\}$ involved, we can choose a new basis, so that $a_{k+1}=(1,0, \ldots, 0), a_{k+\frac{1}{2}}=$ $\left(\theta_{1}, \theta_{2}, 0, \ldots, 0\right)$, and $a_{k}=\left(\sigma_{1}, \sigma_{2}, \sigma_{3}, 0, \ldots, 0\right)$. As $a_{k+\frac{1}{2}}$ and $z_{k+\frac{1}{2}}-z_{k}+\eta F\left(z_{k}\right)$ are co-directed, and $a_{k+1}$ and $z_{k+1}-z_{k}+\eta F\left(z_{k+\frac{1}{2}}\right)$ are co-directed, an important property of this change of basis is that the $E G$ update from $z_{k}$ to $z_{k+1}$ is unconstrained in all coordinates $\ell \geq 4$. More specifically,

$$
z_{k+\frac{1}{2}}[\ell]-z_{k}[\ell]+\eta F\left(z_{k}\right)[\ell]=0, \quad z_{k+1}[\ell]-z_{k}[\ell]+\eta F\left(z_{k+\frac{1}{2}}\right)[\ell]=0, \forall \ell \geq 4 .
$$

Hence, we can represent all of the coordinates $\ell \geq 4$ with one coordinate in the SOS program similar to the unconstrained case. We still need to keep the first three dimensions, but now we only face a problem in dimension 4 rather than in dimension $n$, and we can form a constant size SOS program to search for a certificate of non-negativity for Expression (59).

In Lemma 13, we further simplify the instance that we need to consider. In particular, we argue that it is w.l.o.g. to assume that (1) $a_{k+1}, a_{k+\frac{1}{2}}$, and $a_{k}$ are linear independent and (2) the intersection of the three halfspaces forms a cone, i.e., $b_{k}=b_{k+\frac{1}{2}}=b_{k+1}=0$. Both assumption (1) and (2) reduce the number of variables we need to consider in the SOS program, so a low degree SOS proof is more likely to exist. To maximally reduce the number of variables, we only included the minimal number of constraints that suffice to derive an SOS proof.

Lemma 13 (Simplification Procedure). Let $\mathcal{I}$ be a variational inequality problem for a closed convex set $\mathcal{Z} \subseteq \mathbb{R}^{n}$ and a monotone and L-Lipschitz operator $F: \mathcal{Z} \rightarrow \mathbb{R}^{n}$. Suppose the $E G$ algorithm has a constant step size $\eta$. Let $z_{k}$ be the $k$-th iteration of the EG algorithm, $z_{k+\frac{1}{2}}$ be the $\left(k+\frac{1}{2}\right)$-th iteration as defined in (4), and $z_{k+1}$ be the ( $k+1$ )-th iteration as defined in (5).

Then either $r_{(F, \mathcal{Z})}^{\tan }\left(z_{k}\right) \geq r_{(F, \mathcal{Z})}^{\tan }\left(z_{k+1}\right)$, or there exist vectors $\bar{a}_{k}, \bar{a}_{k+\frac{1}{2}}, \bar{a}_{k+1}, \bar{z}_{k}, \bar{z}_{k+\frac{1}{2}}, \bar{z}_{k+1}, \bar{F}\left(\bar{z}_{k}\right)$, $\bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right), \bar{F}\left(\bar{z}_{k+1}\right) \in \mathbb{R}^{N}$ with $N \leq n+5$ that satisfy the following conditions.

1. $\bar{a}_{k}=\left(\beta_{1}, \beta_{2}, 1,0, \ldots, 0\right), \bar{a}_{k+\frac{1}{2}}=(\alpha, 1,0, \ldots, 0)$, and $\bar{a}_{k+1}=(1,0, \ldots, 0)$ for some $\alpha, \beta_{1}, \beta_{2} \in \mathbb{R}$.
2. $\left\|\bar{F}\left(\bar{z}_{k}\right)-\frac{\left\langle F\left(\bar{z}_{k}\right), \bar{a}_{k}\right\rangle \cdot \bar{a}_{k}}{\left\|\bar{a}_{k}\right\|^{2}}\right\|^{2}-\left\|\bar{F}\left(\bar{z}_{k+1}\right)-\frac{\left\langle\bar{F}\left(\bar{z}_{k+1}\right), \bar{a}_{k+1}\right\rangle \cdot \bar{a}_{k+1}}{\left\|\bar{a}_{k+1}\right\|^{2}} \mathbb{1}\left[\left\langle\bar{F}\left(\bar{z}_{k+1}\right), \bar{a}_{k+1}\right\rangle \geq 0\right]\right\|^{2}<0$.
3. Additionally, $\left\langle\bar{a}_{i}, \bar{z}_{j}\right\rangle \geq 0$ and $\left\langle\bar{a}_{i}, \bar{z}_{i}\right\rangle=0$ for all $i, j \in\left\{k, k+\frac{1}{2}, k+1\right\}$. $\bar{a}_{k+\frac{1}{2}}$ and $\bar{z}_{k+\frac{1}{2}}-\bar{z}_{k}+$ $\eta \bar{F}\left(\bar{z}_{k}\right)$ are co-directed, i.e., they are colinear and have the same direction, and $\bar{a}_{k+1}$ and $\bar{z}_{k+1}-\bar{z}_{k}+$ $\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)$ are co-directed.
4. 

$$
\begin{align*}
\left\|\bar{F}\left(\bar{z}_{k+1}\right)-\bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)\right\|^{2} & \leq L^{2}\left\|\bar{z}_{k+1}-\bar{z}_{k+\frac{1}{2}}\right\|^{2}  \tag{60}\\
\left\langle\bar{F}\left(\bar{z}_{k+1}\right)-\bar{F}\left(\bar{z}_{k}\right), \bar{z}_{k+1}-\bar{z}_{k}\right\rangle & \geq 0  \tag{61}\\
\left\langle\bar{a}_{k}, \bar{F}\left(\bar{z}_{k}\right)\right\rangle & \geq 0 . \tag{62}
\end{align*}
$$

Proof of Lemma 13: For our proof, it will be more convenient to work with terms $r^{\text {tan }}\left(z_{k}\right)^{2}, r^{\text {tan }}\left(z_{k+1}\right)^{2}$ rather than $r^{\text {tan }}\left(z_{k}\right), r^{\tan }\left(z_{k+1}\right)$. Since $r^{\tan }\left(z_{k}\right), r^{\text {tan }}\left(z_{k+1}\right) \geq 0$, then $r^{\text {tan }}\left(z_{k}\right)-$
$r^{\text {tan }}\left(z_{k+1}\right) \geq 0$ iff $r^{\text {tan }}\left(z_{k}\right)^{2}-r^{\text {tan }}\left(z_{k+1}\right)^{2} \geq 0$. For the rest of the proof, we refer to the property that $\bar{a}_{k}=\left(\beta_{1}, \beta_{2}, 1,0, \ldots, 0\right), \bar{a}_{k+\frac{1}{2}}=(\alpha, 1,0, \ldots, 0), \bar{a}_{k+1}=(1,0, \ldots, 0)$ as the form property.

Recall that the $k$-th update of EG is as follows $z_{k+\frac{1}{2}}=\Pi_{\mathcal{Z}}\left[z_{k}-\eta F\left(z_{k}\right)\right]$ and $z_{k+1}=$ $\Pi_{\mathcal{Z}}\left[z_{k}-\eta F\left(z_{k+\frac{1}{2}}\right)\right]$. We define the following vectors:

$$
\begin{align*}
&-a_{k} \in \underset{\substack{a \in \widehat{N}_{z}\left(z_{k}\right),\left\langle F\left(z_{k}\right), a\right\rangle \leq 0}}{\operatorname{argmin}}\left\|F\left(z_{k}\right)-\left\langle F\left(z_{k}\right), a\right\rangle \cdot a\right\|^{2},  \tag{63}\\
& a_{k+\frac{1}{2}}= z_{k+\frac{1}{2}}-z_{k}+\eta F\left(z_{k}\right),  \tag{64}\\
& a_{k+1}= z_{k+1}-z_{k}+\eta F\left(z_{k+\frac{1}{2}}\right) . \tag{65}
\end{align*}
$$

For now, let us assume that $a_{k}, a_{k+\frac{1}{2}}$, and $a_{k+1}$ satisfy (i) the form property, and (ii) $\left\langle a_{k}, z_{k}\right\rangle=$ $\left\langle a_{k+\frac{1}{2}}, z_{k+\frac{1}{2}}\right\rangle=\left\langle a_{k+1}, z_{k+1}\right\rangle=0$. We use this simple case as the basis of our construction, and will remove these assumptions later.

We set $\bar{a}_{k}=a_{k}, \bar{a}_{k+\frac{1}{2}}=a_{k+\frac{1}{2}}, \bar{a}_{k+1}=a_{k+1}, \bar{z}_{k}=z_{k}, \bar{z}_{k+\frac{1}{2}}=z_{k+\frac{1}{2}}, \bar{z}_{k+1}=z_{k+1}, \bar{F}\left(\bar{z}_{k}\right)=F\left(z_{k}\right)$, $\bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)=F\left(z_{k+\frac{1}{2}}\right)$ and $\bar{F}\left(\bar{z}_{k+1}\right)=F\left(z_{k+1}\right)$. We first argue that Property 4 holds. Since $F(\cdot)$ is monotone and $L$-Lipschitz, Inequality (60) and (61) are satisfied. In addition, Inequality (62) is satisfied due to the definition of $a_{k}$.

Next, we show that property 3 holds. By the definition of $\bar{a}_{k+\frac{1}{2}}$ (or $\bar{a}_{k+1}$ ), it is clear that $\bar{a}_{k+\frac{1}{2}}$ (or $\left.\bar{a}_{k+1}\right)$ and $\bar{z}_{k+\frac{1}{2}}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k}\right)\left(\right.$ or $\left.\bar{z}_{k+1}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)\right)$ are co-directed. As $-a_{k} \in \widehat{N}_{\mathcal{Z}}\left(z_{k}\right)$,

$$
\begin{equation*}
\left\langle\bar{a}_{k}, \bar{z}\right\rangle \geq\left\langle\bar{a}_{k}, \bar{z}_{k}\right\rangle=0, \quad \bar{z} \in\left\{\bar{z}_{k}, \bar{z}_{k+\frac{1}{2}}, \bar{z}_{k+1}\right\} \tag{66}
\end{equation*}
$$

According to the update rule of the EG algorithm (Equation (4) and (5)), Equation (64), and Equation (65), we know that for all $z \in \mathcal{Z}$,

$$
\begin{align*}
& \left\langle a_{k+\frac{1}{2}}, z-z_{k+\frac{1}{2}}\right\rangle=\left\langle z_{k+\frac{1}{2}}-z_{k}+\eta F\left(z_{k}\right), z-z_{k+\frac{1}{2}}\right\rangle \geq 0  \tag{67}\\
& \left\langle a_{k+1}, z-z_{k+1}\right\rangle=\left\langle z_{k+1}-z_{k}+\eta F\left(z_{k+\frac{1}{2}}\right), z-z_{k+1}\right\rangle \geq 0 \tag{68}
\end{align*}
$$

which implies that for any $i \in\left\{k+\frac{1}{2}, k+1\right\}, j \in\left\{k, k+\frac{1}{2}, k+1\right\},\left\langle\bar{a}_{i}, \bar{z}_{j}\right\rangle \geq\left\langle\bar{a}_{i}, \bar{z}_{i}\right\rangle=0$.
Finally, we verify Property 2. By Equation (68), $-\frac{a_{k+1}}{\left\|a_{k+1}\right\|} \in \widehat{N}\left(z_{k+1}\right)$, which in combination with Lemma 7 implies

$$
\begin{aligned}
& \left\|\bar{F}\left(\bar{z}_{k+1}\right)-\frac{\left\langle\bar{F}\left(\bar{z}_{k+1}\right), \bar{a}_{k+1}\right\rangle \cdot \bar{a}_{k+1}}{\left\|\bar{a}_{k+1}\right\|^{2}} \mathbb{1}\left[\left\langle\bar{F}\left(\bar{z}_{k+1}\right), \bar{a}_{k+1}\right\rangle \geq 0\right]\right\|^{2} \\
\geq & \min _{\substack{a \in \bar{N}_{\mathcal{Z}}\left(z_{k+1}\right),\left\langle F z_{k+1}\right), a \leq 0}}\left\|F\left(z_{k+1}\right)-\left\langle F\left(z_{k+1}\right), a\right\rangle \cdot a\right\|^{2} \\
= & r^{\tan \left(z_{k+1}\right)^{2} .}
\end{aligned}
$$

According to Lemma 7 and Equation (63), we know that $r^{\tan }\left(z_{k}\right)^{2}=\left\|F\left(z_{k}\right)-\left\langle F\left(z_{k}\right), a_{k}\right\rangle \cdot a_{k}\right\|^{2}=$ $\left\|\bar{F}\left(\bar{z}_{k}\right)-\frac{\left\langle\bar{F}\left(\bar{z}_{k}\right), \bar{a}_{k}\right\rangle \cdot \bar{a}_{k}}{\left\|\bar{a}_{k}\right\|^{2}}\right\|^{2}$. If $r^{\tan }\left(z_{k}\right)^{2}-r^{\tan }\left(z_{k+1}\right)^{2}<0$, then

$$
0>r^{\tan }\left(z_{k}\right)^{2}-r^{\tan }\left(z_{k+1}\right)^{2}
$$

$$
\begin{equation*}
\geq\left\|\bar{F}\left(\bar{z}_{k}\right)-\frac{\left\langle\bar{F}\left(\bar{z}_{k}\right), \bar{a}_{k}\right\rangle \cdot \bar{a}_{k}}{\left\|\bar{a}_{k}\right\|^{2}}\right\|^{2}-\left\|\bar{F}\left(\bar{z}_{k+1}\right)-\frac{\left\langle\bar{F}\left(\bar{z}_{k+1}\right), \bar{a}_{k+1}\right\rangle \cdot \bar{a}_{k+1}}{\left\|\bar{a}_{k+1}\right\|^{2}} \mathbb{1}\left[\left\langle\bar{F}\left(\bar{z}_{k+1}\right), \bar{a}_{k+1}\right\rangle \geq 0\right]\right\|^{2} \tag{69}
\end{equation*}
$$

Observe that when vectors $a_{k}$ and $a_{k+1}$ satisfy the form property, then $\left\|\bar{a}_{k}\right\|=1$, and $\left\|\bar{a}_{k+1}\right\| \geq 1$ and Equation (69) is well-defined.

This completes the proof for the case, where (i) vectors $a_{k}, a_{k+\frac{1}{2}}$, and $a_{k+1}$ satisfy the form property, and (ii) $\left\langle a_{k}, z_{k}\right\rangle=\left\langle a_{k+\frac{1}{2}}, z_{k+\frac{1}{2}}\right\rangle=\left\langle a_{k+1}, z_{k+1}\right\rangle=0$. Our next step is to remove the assumptions. We first show how to modify the construction so that for any $a_{k}, a_{k+\frac{1}{2}}, a_{k+1}$, we can construct vectors $\hat{a}_{k}, \hat{a}_{k+\frac{1}{2}}, \hat{a}_{k+1}, \hat{z}_{k}, \hat{z}_{k+\frac{1}{2}}, \hat{z}_{k+1}, \widehat{F}\left(\hat{z}_{k}\right), \widehat{F}\left(\hat{z}_{k+\frac{1}{2}}\right), \widehat{F}\left(\hat{z}_{k+1}\right) \in \mathbb{R}^{n+5}$, that satisfy, among other properties, (a) $\left\langle\hat{a}_{k}, \hat{z}_{k}\right\rangle=\left\langle\hat{a}_{k+\frac{1}{2}}, \hat{z}_{k+\frac{1}{2}}\right\rangle=\left\langle\hat{a}_{k+1}, \hat{z}_{k+1}\right\rangle=0$, and (b) vectors $\hat{a}_{k}, \hat{a}_{k+\frac{1}{2}}, \hat{a}_{k+1}$ are linear independent. In our final step, we choose a proper basis to construct vectors $\bar{a}_{k}, \bar{a}_{k+\frac{1}{2}}, \bar{a}_{k+1}, \bar{z}_{k}, \bar{z}_{k+\frac{1}{2}}, \bar{z}_{k+1}$, $\bar{F}\left(\bar{z}_{k}\right), \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right), \bar{F}\left(\bar{z}_{k+1}\right) \in \mathbb{R}^{n+5}$ that satisfy all four properties in the statement of Lemma 13.

We now present the construction of vectors $\hat{a}_{k}, \hat{a}_{k+\frac{1}{2}}, \hat{a}_{k+1}, \hat{z}_{k}, \hat{z}_{k+\frac{1}{2}}, \hat{z}_{k+1}, \widehat{F}\left(\hat{z}_{k}\right), \widehat{F}\left(\hat{z}_{k+\frac{1}{2}}\right), \widehat{F}\left(\hat{z}_{k+1}\right)$. High-levelly speaking, we introduce five dummy dimensions. The purpose of the first dummy dimension is to ensure property (a). We use the remaining four dummy dimensions to ensure that the newly created vectors $\hat{a}_{k}, \hat{a}_{k+\frac{1}{2}}$ and $\hat{a}_{k+1}$ are linearly independent satisfying property (b). More specifically for parameters $\ell, \epsilon>0$ that we determine later, we define $\hat{z}_{k}, \hat{z}_{k+\frac{1}{2}}, \hat{z}_{k+1}, \widehat{F}\left(\hat{z}_{k}\right), \widehat{F}\left(\hat{z}_{k+\frac{1}{2}}\right)$, $\widehat{F}\left(\hat{z}_{k+1}\right), \hat{a}_{k}, \hat{a}_{k+\frac{1}{2}}, \hat{a}_{k+1}$ as follows

$$
\begin{align*}
& \hat{z}_{i}:=\left(-\epsilon^{-1}, 0,0,0,0, z_{i}\right) \quad \forall i \in\left\{k, k+\frac{1}{2}, k+1\right\}  \tag{70}\\
& \widehat{F}\left(\hat{z}_{k}\right):=\left(\frac{\epsilon}{\eta} \cdot\left\langle a_{k+\frac{1}{2}}, z_{k+\frac{1}{2}}\right\rangle, 0, \frac{\epsilon}{\eta}, 0, \frac{\ell \epsilon}{\eta}, F\left(z_{k}\right)\right)  \tag{71}\\
& \widehat{F}\left(\hat{z}_{k+\frac{1}{2}}\right):=\left(\frac{\epsilon}{\eta} \cdot\left\langle a_{k+1}, z_{k+1}\right\rangle, 0,0, \frac{\epsilon}{\eta}, \frac{\ell \epsilon}{\eta}, F\left(z_{k+\frac{1}{2}}\right)\right)  \tag{72}\\
& \widehat{F}\left(\hat{z}_{k+1}\right):=\left(\frac{\epsilon}{\eta} \cdot\left\langle a_{k+1}, z_{k+1}\right\rangle, 0,0, \frac{\epsilon}{\eta}, \frac{\ell \epsilon}{\eta}, F\left(z_{k+1}\right)\right)  \tag{73}\\
& \hat{a}_{k}:=\left(\epsilon \cdot\left\langle a_{k}, z_{k}\right\rangle, \epsilon, 0,0, \ell \epsilon, a_{k}\right)  \tag{74}\\
& \hat{a}_{k+\frac{1}{2}}:=\left(\epsilon \cdot\left\langle a_{k+\frac{1}{2}}, z_{k+\frac{1}{2}}\right\rangle, 0, \epsilon, 0, \ell \epsilon, a_{k+\frac{1}{2}}\right)  \tag{75}\\
& \hat{a}_{k+1}:=\left(\epsilon \cdot\left\langle a_{k+1}, z_{k+1}\right\rangle, 0,0, \epsilon, \ell \epsilon, a_{k+1}\right) \tag{76}
\end{align*}
$$

Clearly, $\hat{a}_{k}, \hat{a}_{k+\frac{1}{2}}, \hat{a}_{k+1}$ are linear independent, $\hat{a}_{k+1}$ and $\hat{z}_{k+1}-\hat{z}_{k}+\eta \widehat{F}\left(\hat{z}_{k+\frac{1}{2}}\right)$ are co-directed, and $\hat{a}_{k+\frac{1}{2}}$ and $\hat{z}_{k+\frac{1}{2}}-\hat{z}_{k}+\eta \widehat{F}\left(\hat{z}_{k}\right)$ are co-directed. Note that the following inequalites hold. By

Equation (63)-(65), it is clear that $-a_{k} \in \widehat{N}\left(z_{k}\right) \subseteq N\left(z_{k}\right),-a_{k+\frac{1}{2}} \in N\left(z_{k+\frac{1}{2}}\right)$ and $-a_{k+1} \in N\left(z_{k+1}\right)$, which further implies

$$
\begin{align*}
& \left\langle\hat{a}_{i}, \hat{z}_{j}\right\rangle=\left\langle a_{i}, z_{j}\right\rangle-\left\langle a_{i}, z_{i}\right\rangle \geq 0, \quad \forall i, j \in\left\{k, k+\frac{1}{2}, k+1\right\}  \tag{77}\\
& \left\langle\hat{a}_{i}, \hat{z}_{i}\right\rangle=0, \quad \forall i \in\left\{k, k+\frac{1}{2}, k+1\right\}  \tag{78}\\
& \left\|\widehat{F}\left(\hat{z}_{k+1}\right)-\widehat{F}\left(\hat{z}_{k+\frac{1}{2}}\right)\right\|^{2}=\left\|F\left(z_{k+1}\right)-F\left(z_{k+\frac{1}{2}}\right)\right\|^{2} \leq L^{2}\left\|z_{k+1}-z_{k+\frac{1}{2}}\right\|^{2}=\left\|\hat{z}_{k+1}-\hat{z}_{k+\frac{1}{2}}\right\|^{2}  \tag{79}\\
& \left\langle\widehat{F}\left(\hat{z}_{k+1}\right)-\widehat{F}\left(\hat{z}_{k}\right), \hat{z}_{k+1}-\hat{z}_{k}\right\rangle=\left\langle F\left(z_{k+1}\right)-F\left(z_{k}\right), z_{k+1}-z_{k}\right\rangle \geq 0 \tag{80}
\end{align*}
$$

Moreover, $\left\langle\hat{a}_{k}, \widehat{F}\left(\hat{z}_{k}\right)\right\rangle=\frac{\epsilon^{2}}{\eta} \cdot\left(\left\langle a_{k}, z_{k}\right\rangle\left\langle a_{k+\frac{1}{2}}, z_{k+\frac{1}{2}}\right\rangle+\ell^{2}\right)+\left\langle a_{k}, F\left(z_{k}\right)\right\rangle$. We choose $\ell$ to be sufficiently large so that $\left\langle a_{k}, z_{k}\right\rangle\left\langle a_{k+\frac{1}{2}}, z_{k+\frac{1}{2}}\right\rangle+\ell^{2} \geq 0$. Hence, for our choice of $\ell$,

$$
\begin{equation*}
\left\langle\hat{a}_{k}, \widehat{F}\left(\hat{z}_{k}\right)\right\rangle \geq\left\langle a_{k}, F\left(z_{k}\right)\right\rangle \geq 0 . \tag{81}
\end{equation*}
$$

We define function

$$
\begin{aligned}
\widehat{H}\left(\hat{z}_{k}\right) & :=\left\|\widehat{F}\left(\hat{z}_{k}\right)-\frac{\left\langle\widehat{F}\left(\hat{z}_{k}\right), \hat{a}_{k}\right\rangle}{\left\|\hat{a}_{k}\right\|^{2}} \cdot \hat{a}_{k}\right\|^{2} \\
& =\left\|\widehat{F}\left(\hat{z}_{k}\right)-\frac{\frac{\epsilon^{2}}{\eta} \cdot\left(\left\langle a_{k}, z_{k}\right\rangle\left\langle a_{k+\frac{1}{2}}, z_{k+\frac{1}{2}}\right\rangle+\ell^{2}\right)+\left\langle a_{k}, F\left(z_{k}\right)\right\rangle}{\epsilon^{2}\left(\left\langle a_{k}, z_{k}\right\rangle^{2}+1+\ell^{2}\right)+\left\|a_{k}\right\|^{2}} \cdot \hat{a}_{k}\right\|^{2} .
\end{aligned}
$$

Define $f(\epsilon):=\frac{\frac{\epsilon^{2}}{\eta} \cdot\left(\left\langle a_{k}, z_{k}\right\rangle\left\langle a_{k+\frac{1}{2}}, z_{k+\frac{1}{2}}\right\rangle+\ell^{2}\right)+\left\langle a_{k}, F\left(z_{k}\right)\right\rangle}{\epsilon^{2}\left(\left\langle a_{k}, z_{k}\right\rangle^{2}+1+\ell^{2}\right)+\left\|a_{k}\right\|^{2}}$. We can simplify $\widehat{H}\left(\hat{z}_{k}\right)$ to be

$$
\epsilon^{2} \cdot\left\|\left(\frac{\left\langle a_{k+\frac{1}{2}}, z_{k+\frac{1}{2}}\right\rangle}{\eta}-f(\epsilon)\left\langle a_{k}, z_{k}\right\rangle,-f(\epsilon), \frac{1}{\eta}, 0, \frac{\ell}{\eta}-f(\epsilon) \ell\right)\right\|^{2}+\left\|F\left(z_{k}\right)-f(\epsilon) \cdot a_{k}\right\|^{2} .
$$

When $a_{k}=(0, \ldots, 0), r^{t a n}\left(z_{k}\right)^{2}=\left\|F\left(z_{k}\right)\right\|^{2}$ (Equation (63)) and $f(\epsilon)=\frac{\ell^{2}}{\eta\left(1+\ell^{2}\right)}$ for any $\epsilon>$ 0 . Therefore, $\lim _{\epsilon \rightarrow 0^{+}} \widehat{H}\left(\hat{z}_{k}\right)=\left\|F\left(z_{k}\right)\right\|^{2}=r^{\tan }\left(z_{k}\right)^{2}$, when $a_{k}=(0, \ldots, 0)$. When $a_{k} \neq$ $(0, \ldots, 0), r^{t a n}\left(z_{k}\right)^{2}=\left\|F\left(z_{k}\right)-\frac{\left\langle a_{k} F\left(z_{k}\right)\right\rangle}{\left\|a_{k}\right\|^{2}} \cdot a_{k}\right\|^{2}$ (Equation (63)) and $\lim _{\epsilon \rightarrow 0^{+}} f(\epsilon)=\frac{\left\langle a_{k}, F\left(z_{k}\right)\right\rangle}{\left\|a_{k}\right\|^{2}}$, so $\lim _{\epsilon \rightarrow 0^{+}} \widehat{H}\left(\hat{z}_{k}\right)=\left\|F\left(z_{k}\right)-\frac{\left\langle a_{k}, F\left(z_{k}\right)\right\rangle}{\left\|a_{k}\right\|^{2}} \cdot a_{k}\right\|^{2}=r^{\tan }\left(z_{k}\right)^{2}$.

Similarly, we define function

$$
\begin{aligned}
\widehat{H}\left(\hat{z}_{k+1}\right) & \left.:=\| \widehat{F}\left(\hat{z}_{k+1}\right)-\frac{\left\langle\widehat{F}\left(\hat{z}_{k+1}\right), \hat{a}_{k+1}\right\rangle \cdot \hat{a}_{k+1}}{\left\|\hat{a}_{k+1}\right\|^{2}} \mathbb{1}\left[\widehat{F}\left(\hat{z}_{k+1}\right), \hat{a}_{k+1}\right\rangle \geq 0\right] \|^{2} \\
& =\left\|\widehat{F}\left(\hat{z}_{k+1}\right)-\frac{\frac{\epsilon^{2}}{\eta} \cdot\left(\left\langle a_{k+1}, z_{k+1}\right\rangle^{2}+1+\ell^{2}\right)+\left\langle F\left(z_{k+1}\right), a_{k+1}\right\rangle}{\epsilon^{2}\left(\left\langle a_{k+1}, z_{k+1}\right\rangle^{2}+1+\ell^{2}\right)+\left\|a_{k+1}\right\|^{2}} \cdot \hat{a}_{k+1} \mathbb{1}\left[\left\langle\widehat{F}\left(\hat{z}_{k+1}\right), \hat{a}_{k+1}\right\rangle \geq 0\right]\right\|^{2} .
\end{aligned}
$$

Define $g(\epsilon):=\frac{\frac{\epsilon^{2}}{\eta} \cdot\left(\left\langle a_{k+1}, z_{k+1}\right\rangle^{2}+1+\ell^{2}\right)+\left\langle F\left(z_{k+1}\right), a_{k+1}\right\rangle}{\epsilon^{2}\left\langle\left\langle a_{k+1}, z_{k+1}\right\rangle^{2}+1+\ell^{2}\right)+\left\|a_{k+1}\right\|^{2}}$, and we can simplify $\widehat{H}\left(\hat{z}_{k+1}\right)$ to be

$$
\begin{aligned}
\epsilon^{2}\left(\frac{1}{\eta}-g(\epsilon) \mathbb{1}\left[\left\langle\widehat{F}\left(\hat{z}_{k+1}\right), \hat{a}_{k+1}\right\rangle \geq 0\right]\right)^{2} \cdot & \left\|\left(\left\langle a_{k+1}, z_{k+1}\right\rangle, 0,0,1, \ell\right)\right\|^{2} \\
+ & \left\|F\left(z_{k+1}\right)-g(\epsilon) \cdot a_{k+1} \mathbb{\mathbb { 1 }}\left[\left\langle\widehat{F}\left(\hat{z}_{k+1}\right), \hat{a}_{k+1}\right\rangle \geq 0\right]\right\|^{2}
\end{aligned}
$$

When $a_{k+1}=(0, \ldots, 0)$, we have $g(\epsilon)=\frac{1}{\eta}$ and $\left\langle\widehat{F}\left(\hat{z}_{k+1}\right), \hat{a}_{k+1}\right\rangle \geq 0$, so $\widehat{H}\left(\hat{z}_{k+1}\right)=$ $\left\|F\left(z_{k+1}\right)\right\|^{2} \geq r^{\tan }\left(z_{k+1}\right)^{2}$. When $a_{k+1} \neq(0, \ldots, 0)$, we have $\lim _{\epsilon \rightarrow 0^{+}} g(\epsilon)=\frac{\left\langle F\left(z_{k+1}\right), a_{k+1}\right\rangle}{\left\|a_{k+1}\right\|^{2}}$ and $\lim _{\epsilon \rightarrow 0^{+}} \mathbb{1}\left[\left\langle\widehat{F}\left(\hat{z}_{k+1}\right), \hat{a}_{k+1}\right\rangle \geq 0\right]=\mathbb{1}\left[\left\langle F\left(z_{k+1}\right), a_{k+1}\right\rangle \geq 0\right]$, 15 hence

$$
\lim _{\epsilon \rightarrow 0^{+}} \widehat{H}\left(\hat{z}_{k+1}\right)=\left\|F\left(z_{k+1}\right)-\frac{\left\langle F\left(z_{k+1}\right), a_{k+1}\right\rangle}{\left\|a_{k+1}\right\|^{2}} \cdot a_{k+1} \mathbb{1}\left[\left\langle F\left(z_{k+1}\right), a_{k+1}\right\rangle \geq 0\right]\right\|^{2} \geq r^{\tan }\left(z_{k+1}\right)^{2} .
$$

The last inequality is because $\frac{-a_{k+1}}{\left\|a_{k+1}\right\|} \in \widehat{N}_{\mathcal{Z}}\left(z_{k+1}\right)$ and Lemma 7 .
If $r^{\text {tan }}\left(z_{k}\right)^{2}-r^{\text {tan }}\left(z_{k+1}\right)^{2}<0$, then

$$
\lim _{\epsilon \rightarrow 0^{+}}\left(\widehat{H}\left(\hat{z}_{k}\right)-\widehat{H}\left(\hat{z}_{k+1}\right)\right) \leq r^{\tan }\left(z_{k}\right)^{2}-r^{\tan }\left(z_{k+1}\right)^{2}<0 .
$$

Thus, we can choose a sufficiently small $\epsilon$ so that $\hat{H}\left(\hat{z}_{k}\right)-\hat{H}\left(\hat{z}_{k+1}\right)<0$. Together with Inequalities (77)-(81), we can satisfy all properties excluding the form property using $\hat{z}_{k}, \hat{z}_{k+\frac{1}{2}}, \hat{z}_{k+1}, \hat{a}_{k}$, $\hat{a}_{k+\frac{1}{2}}, \hat{a}_{k+1}, \widehat{F}\left(\hat{z}_{k}\right), \widehat{F}\left(\hat{z}_{k+\frac{1}{2}}\right), \widehat{F}\left(\hat{z}_{k+1}\right)$.

Now we show how to make the vectors also satisfy the form property. We perform a change of basis so that vectors $\hat{a}_{k}, \hat{a}_{k+\frac{1}{2}}$ and $\hat{a}_{k+1}$ only depend on the first three coordinates. We use the Gram-Schmidt process to generate a basis, where vectors $\hat{a}_{k}, \hat{a}_{k+\frac{1}{2}}, \hat{a}_{k+1}$ all lie in the span of the first three vector of the new basis. More formally, let $N=n+5$ and $\left\{b_{i}\right\}_{i \in[N]}$ be a sequence of orthonormal vectors produced by the Gram-Schmidt process on ordered input $\hat{a}_{k+1}, \hat{a}_{k+\frac{1}{2}}, \hat{a}_{k}$ and $\left\{e_{i}\right\}_{i \in[N]}$. Let $Q$ be the $N \times N$ matrix, where the $i$-th row of $Q$ is vector $b_{i}$. Observe that any vector $z \in \mathbb{R}^{N}$ written in the basis $\left\{e_{i}\right\}_{i \in[N]}$ can be represented by the basis $\left\{b_{i}\right\}_{i \in[N]}$ with coefficients $Q \cdot z$.

Let $\bar{a}_{k}=Q \cdot \hat{a}_{k}, \bar{a}_{k+\frac{1}{2}}=Q \cdot \hat{a}_{k+\frac{1}{2}}, \bar{a}_{k+1}=Q \cdot \hat{a}_{k+1}, \bar{z}_{k}=Q \cdot \hat{z}_{k}, \bar{z}_{k+\frac{1}{2}}=Q \cdot \hat{z}_{k+\frac{1}{2}}, \bar{z}_{k+1}=Q \cdot \hat{z}_{k+1}$, $\bar{F}\left(\bar{z}_{k}\right)=Q \cdot \widehat{F}\left(\hat{z}_{k}\right), \bar{F}\left(\bar{z}_{k+\frac{1}{2}}^{2}\right)=Q \cdot \widehat{F}\left(\hat{z}_{k+\frac{1}{2}}\right)$ and $\bar{F}\left(\bar{z}_{k+1}\right)=Q \cdot \widehat{F}\left(\hat{z}_{k+1}\right)$. Note that $\bar{a}_{k}$ is the coefficients of $\hat{a}_{k}$ written in the basis $\left\{b_{i}\right\}_{i \in[N]}$ and similar reasoning holds for the rest of the defined vectors. Clearly, for any $\hat{z}, \hat{z}^{\prime} \in \mathbb{R}^{N}$, if we define $\bar{z}=Q \cdot \hat{z}$ and $\bar{z}^{\prime}=Q \cdot \hat{z}^{\prime}$, then we have

$$
\begin{equation*}
\left\langle\bar{z}, \bar{z}^{\prime}\right\rangle=\left\langle\hat{z}, \hat{z}^{\prime}\right\rangle . \tag{82}
\end{equation*}
$$

[^15]Combining Equation (82) and the fact that all properties but the form property hold for vectors $\hat{a}_{k}$, $\hat{a}_{k+\frac{1}{2}}, \hat{a}_{k+1}, \hat{z}_{k}, \hat{z}_{k+\frac{1}{2}}, \hat{z}_{k+1}, \widehat{F}\left(\hat{z}_{k}\right), \widehat{F}\left(\hat{z}_{k+\frac{1}{2}}\right)$ and $\widehat{F}\left(\hat{z}_{k+1}\right)$, we conclude that the same properties also hold for vectors $\bar{a}_{k}, \bar{a}_{k+\frac{1}{2}}, \bar{a}_{k+1}, \bar{z}_{k}, \bar{z}_{k+\frac{1}{2}}, \bar{z}_{k+1}, \bar{F}\left(\bar{z}_{k}\right), \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)$ and $\bar{F}\left(\bar{z}_{k+1}\right)$.

Finally, by properties of the Gram-Schmidt process, the order of the vector in its input, and the fact that vectors $\hat{a}_{k}, \hat{a}_{k+\frac{1}{2}}$ and $\hat{a}_{k+1}$ are linearly independent, we have $\hat{a}_{k+1} \in \operatorname{Span}\left(b_{1}\right)$, $\hat{a}_{k+\frac{1}{2}} \in \operatorname{Span}\left(b_{1}, b_{2}\right), \hat{a}_{k} \in \operatorname{Span}\left(b_{1}, b_{2}, b_{3}\right),\left\langle\hat{a}_{k+1}, b_{1}\right\rangle>0,\left\langle\hat{a}_{k+\frac{1}{2}}, b_{2}\right\rangle>0$ and $\left\langle\hat{a}_{k}, b_{3}\right\rangle>0$. Thus $\bar{a}_{k}=\left(\beta_{1}, \beta_{2}, b, 0, \ldots, 0\right), \bar{a}_{k+\frac{1}{2}}=(\alpha, c, 0, \ldots, 0)$ and $\bar{a}_{k+1}=(d, 0, \ldots, 0)$, where $\beta_{1}, \beta_{2}, \alpha \in \mathbb{R}$ and $b, c, d>0$. By properly scaling $\bar{a}_{k}, \bar{a}_{k+\frac{1}{2}}$ and $\bar{a}_{k+1}$, we can make them satisfy the form property. This completes the proof.

In Theorem 9, we establish the monotonicity of the tangent residual. Our proof is based on the solution to the degree-8 SOS program concerning polynomials in 27 variables.

Theorem 9. Let $\mathcal{Z} \subseteq \mathbb{R}^{n}$ be a closed convex set and $F: \mathcal{Z} \rightarrow \mathbb{R}^{n}$ be a monotone and L-Lipschitz operator. For any step size $\eta \in\left(0, \frac{1}{L}\right)$ and any $z_{k} \in \mathcal{Z}$, the $E G$ method update satisfies $r_{(F, \mathcal{Z})}^{t a n}\left(z_{k}\right) \geq r_{(F, \mathcal{Z})}^{t a n}\left(z_{k+1}\right)$.
Proof of Theorem 9: Assume towards contradiction that $r^{\tan }\left(z_{k+1}\right)>r^{\tan }\left(z_{k}\right)$, using Lemma 13 there exists numbers $\alpha, \beta_{1}, \beta_{2} \in \mathbb{R}$ and vectors $\bar{a}_{k}, \bar{a}_{k+\frac{1}{2}}, \bar{a}_{k+1}, \bar{z}_{k}, \bar{z}_{k+\frac{1}{2}}, \bar{z}_{k+1}, \bar{F}\left(\bar{z}_{k}\right), \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)$, $\bar{F}\left(\bar{z}_{k+1}\right) \in \mathbb{R}^{N}$ where $N=n+5$ that satisfy the properties in the statement of Lemma 13 and

$$
\begin{aligned}
0 & >\left\|\bar{F}\left(\bar{z}_{k}\right)-\frac{\left\langle F\left(\bar{z}_{k}\right), \bar{a}_{k}\right\rangle}{\left\|\bar{a}_{k}\right\|^{2}} \bar{a}_{k}\right\|^{2}-\left\|\bar{F}\left(\bar{z}_{k+1}\right)-\frac{\left\langle\bar{F}\left(\bar{z}_{k+1}\right), \bar{a}_{k+1}\right\rangle \bar{a}_{k+1}}{\left\|\bar{a}_{k+1}\right\|^{2}} \mathbb{1}\left[\left\langle\bar{F}\left(\bar{z}_{k+1}\right), \bar{a}_{k+1}\right\rangle \geq 0\right]\right\|^{2} \\
& =\left\|\bar{F}\left(\bar{z}_{k}\right)\right\|^{2}-\left\|\bar{F}\left(\bar{z}_{k+1}\right)\right\|^{2}-\frac{\left(\beta_{1} \bar{F}\left(\bar{z}_{k}\right)[1]+\beta_{2} \bar{F}\left(\bar{z}_{k}\right)[2]+\bar{F}\left(\bar{z}_{k}\right)[3]\right)^{2}}{\beta_{1}^{2}+\beta_{2}^{2}+1}+\bar{F}\left(\bar{z}_{k+1}\right)[1]^{2} \mathbb{1}\left[\bar{F}\left(\bar{z}_{k+1}\right)[1] \geq 0\right],
\end{aligned}
$$

where we use the fact that $\bar{a}_{k}=\left(\beta_{1}, \beta_{2}, 1,0, \ldots, 0\right)$ and $\bar{a}_{k+1}=(1,0, \ldots, 0)$.
We use Target to denote

$$
\left\|\bar{F}\left(\bar{z}_{k}\right)\right\|^{2}-\left\|\bar{F}\left(\bar{z}_{k+1}\right)\right\|^{2}-\frac{\left(\beta_{1} \bar{F}\left(\bar{z}_{k}\right)[1]+\beta_{2} \bar{F}\left(\bar{z}_{k}\right)[2]+\bar{F}\left(\bar{z}_{k}\right)[3]\right)^{2}}{\beta_{1}^{2}+\beta_{2}^{2}+1}+\bar{F}\left(\bar{z}_{k+1}\right)[1]^{2} \mathbb{1}\left[\bar{F}\left(\bar{z}_{k+1}\right)[1] \geq 0\right]
$$

and our goal is to show that TARGET is non-negative, and thus reach a contradiction.
Our plan is to show that we can obtain a sum of quotients of SOS polynomials by adding nonpositive terms to TARGET, which implies the non-negativity of TARGET. We add the non-positive terms in a few steps.

Combining Lemma 13 and the fact that $\eta>0$ and $(\eta L)^{2} \leq 1$, we derive the following two inequalities:

$$
\begin{array}{r}
\left\langle\eta \bar{F}\left(\bar{z}_{k+1}\right)-\eta \bar{F}\left(\bar{z}_{k}\right), \bar{z}_{k}-\bar{z}_{k+1}\right\rangle \leq 0, \\
\left\|\eta \bar{F}\left(\bar{z}_{k+1}\right)-\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)\right\|^{2}-\left\|\bar{z}_{k+1}-\bar{z}_{k+\frac{1}{2}}\right\|^{2} \leq 0 . \tag{84}
\end{array}
$$

Equipped with these two inequalities, it is clear that

$$
\begin{equation*}
\eta^{2} \cdot \text { TARGET } \geq \eta^{2} \cdot \text { TARGET }+2 \cdot \text { LHS of Inequality (83) }+ \text { LHS of Inequality (84). } \tag{85}
\end{equation*}
$$

Therefore, it is sufficient to show that the RHS of Inequality (85) is non-negative.
We take advantage of the sparsity of vectors $\bar{a}_{k}, \bar{a}_{k+\frac{1}{2}}, \bar{a}_{k+1}$ by considering the following partition of $[N]$. We define $P_{1}=\{1,2,3\}$ and $P_{2}=\{4,5, \cdots, N\}$. For any vector $z \in \mathbb{R}^{N}$ and $j \in\{1,2\}$, we define $p_{j}(z) \in \mathbb{R}^{n}$ to be the vector such that $p_{j}(z)[i]=z[i]$ for $i \in P_{j}$ and $p_{j}(z)[i]=0$ otherwise. We divide the RHS of Inequality (85) using the partition to Expression (86) and Expression (87):

$$
\begin{align*}
& \eta^{2}\left\|p_{2}\left(\bar{F}\left(\bar{z}_{k}\right)\right)\right\|^{2}-\eta^{2}\left\|p_{2}\left(\bar{F}\left(\bar{z}_{k+1}\right)\right)\right\|^{2}+2 \eta\left\langle p_{2}\left(\bar{F}\left(\bar{z}_{k+1}\right)\right)-p_{2}\left(\bar{F}\left(\bar{z}_{k}\right)\right), p_{2}\left(\bar{z}_{k}\right)-p_{2}\left(\bar{z}_{k+1}\right)\right\rangle \\
& \quad+\eta^{2}\left\|p_{2}\left(\bar{F}\left(\bar{z}_{k+1}\right)\right)-p_{2}\left(\bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)\right)\right\|^{2}-\left\|p_{2}\left(\bar{z}_{k+1}\right)-p_{2}\left(\bar{z}_{k+\frac{1}{2}}\right)\right\|^{2}, \tag{86}
\end{align*}
$$

and

$$
\begin{align*}
& \eta^{2}\left\|p_{1}\left(\bar{F}\left(\bar{z}_{k}\right)\right)\right\|^{2}-\eta^{2}\left\|p_{1}\left(\bar{F}\left(\bar{z}_{k+1}\right)\right)\right\|^{2}+2 \eta\left\langle p_{1}\left(\bar{F}\left(\bar{z}_{k+1}\right)\right)-p_{1}\left(\bar{F}\left(\bar{z}_{k}\right)\right), p_{1}\left(\bar{z}_{k}\right)-p_{1}\left(\bar{z}_{k+1}\right)\right\rangle \\
& \quad+\eta^{2}\left\|p_{1}\left(\bar{F}\left(\bar{z}_{k+1}\right)\right)-p_{1}\left(\bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)\right)\right\|^{2}-\left\|p_{1}\left(\bar{z}_{k+1}\right)-p_{1}\left(\bar{z}_{k+\frac{1}{2}}\right)\right\|^{2} \\
& \quad-\frac{\eta^{2}}{\beta_{1}^{2}+\beta_{2}^{2}+1}\left(\beta_{1} \bar{F}\left(\bar{z}_{k}\right)[1]+\beta_{2} \bar{F}\left(\bar{z}_{k}\right)[2]+\bar{F}\left(\bar{z}_{k}\right)[3]\right)^{2}+\eta^{2} \bar{F}\left(\bar{z}_{k+1}\right)[1]^{2} \mathbb{1}\left[\bar{F}\left(\bar{z}_{k+1}\right)[1] \geq 0\right] \tag{87}
\end{align*}
$$

First we show that the Expression (86) is non-negative. According to Lemma 13, $\bar{a}_{k+\frac{1}{2}}$ and $\bar{z}_{k+\frac{1}{2}}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k}\right)$ are co-directed, and $\bar{a}_{k+1}$ and $\bar{z}_{k+1}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)$ are co-directed. For any $i \in P_{2}$, we know $\bar{a}_{k+\frac{1}{2}}[i]=\bar{a}_{k+1}[i]=0$ and thus we have

$$
\begin{array}{r}
0=\left\langle e_{i}, \bar{a}_{k+\frac{1}{2}}\right\rangle=\left\langle e_{i}, \bar{z}_{k+\frac{1}{2}}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k+1}\right)\right\rangle \Leftrightarrow \bar{z}_{k+\frac{1}{2}}[i]=\bar{z}_{k}[i]-\eta \bar{F}\left(\bar{z}_{k+1}\right)[i], \\
0=\left\langle e_{i}, \bar{a}_{k+1}\right\rangle=\left\langle e_{i}, \bar{z}_{k+1}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k+1}\right)\right\rangle \Leftrightarrow \bar{z}_{k+1}[i]=\bar{z}_{k}[i]-\eta \bar{F}\left(\bar{z}_{k+1}\right)[i],
\end{array}
$$

which implies that

$$
\begin{aligned}
& p_{2}\left(\bar{z}_{k+\frac{1}{2}}\right)=p_{2}\left(\bar{z}_{k}\right)-\eta \cdot p_{2}\left(\bar{F}\left(\bar{z}_{k}\right)\right), \\
& p_{2}\left(\bar{z}_{k+1}\right)=p_{2}\left(\bar{z}_{k}\right)-\eta \cdot p_{2}\left(\bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)\right) .
\end{aligned}
$$

Intuitively, one can think of the coordinates in $P_{2}$ as the ones where the EG update is unconstrained. With the two new equalities, it is easy to verify that Expression (86) is always 0 .

$$
\begin{aligned}
& \quad \eta^{2}\left\|p_{2}\left(\bar{F}\left(\bar{z}_{k}\right)\right)\right\|^{2}-\eta^{2}\left\|p_{2}\left(\bar{F}\left(\bar{z}_{k+1}\right)\right)\right\|^{2}+2 \eta\left\langle p_{2}\left(\bar{F}\left(\bar{z}_{k+1}\right)\right)-p_{2}\left(\bar{F}\left(\bar{z}_{k}\right)\right), p_{2}\left(\bar{z}_{k}\right)-p_{2}\left(\bar{z}_{k+1}\right)\right\rangle \\
& \quad+\quad \eta^{2}\left\|p_{2}\left(\bar{F}\left(\bar{z}_{k+1}\right)\right)-p_{2}\left(\bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)\right)\right\|^{2}-\left\|p_{2}\left(\bar{z}_{k+1}\right)-p_{2}\left(\bar{z}_{k+\frac{1}{2}}\right)\right\|^{2} \\
& = \\
& =\eta^{2}\left\|p_{2}\left(\bar{F}\left(\bar{z}_{k}\right)\right)\right\|^{2}-\eta^{2}\left\|p_{2}\left(\bar{F}\left(\bar{z}_{k+1}\right)\right)\right\|^{2}+2 \eta^{2}\left\langle p_{2}\left(\bar{F}\left(\bar{z}_{k+1}\right)\right)-p_{2}\left(\bar{F}\left(\bar{z}_{k}\right)\right), p_{2}\left(\bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)\right)\right\rangle \\
& \quad+\quad \eta^{2}\left\|p_{2}\left(\bar{F}\left(\bar{z}_{k+1}\right)\right)-p_{2}\left(\bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)\right)\right\|^{2}-\eta^{2} \| p_{2}\left(\bar{F}\left(\bar{z}_{k}\right)-p_{2}\left(\bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)\right) \|^{2}\right. \\
& =0 .
\end{aligned}
$$

We now turn our attention to Expression (87) and show that it is non-negative. The analysis is more challenging here. We introduce the following six non-positive expressions, multiply each of them with a carefully chosen coefficient, then add them together with Expression (87). We finally verify that the sum is a sum of quotients of SOS polynomials implying the non-negativity of Expression (87). We believe it will be extremely challenging if not impossible for human beings to discover these non-positive expressions and their associated coefficients manually to complete this proof. We instead harness the power of the SOS programming to overcome the difficulty and make the discovery.

We first present the six non-positive expressions.

$$
\begin{align*}
& \bar{z}_{k+\frac{1}{2}}[1]\left(\left(\bar{z}_{k+\frac{1}{2}}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k}\right)\right)[1]-\alpha\left(\bar{z}_{k+\frac{1}{2}}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k}\right)\right)[2]\right)=0,  \tag{88}\\
& \bar{z}_{k+1}[2]\left(\left(\bar{z}_{k+\frac{1}{2}}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k}\right)\right)[1]-\alpha\left(\bar{z}_{k+\frac{1}{2}}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k}\right)\right)[2]\right)=0,  \tag{89}\\
&\left(\alpha\left(\bar{z}_{k}-\eta \bar{F}\left(\bar{z}_{k}\right)\right)[1]+\left(\bar{z}_{k}-\eta \bar{F}\left(\bar{z}_{k}\right)\right)[2]\right)\left(\alpha \bar{z}_{k+1}[1]+\bar{z}_{k+1}[2]\right) \leq 0,  \tag{90}\\
&-\eta\left(\beta_{1} \bar{F}\left(\bar{z}_{k}\right)[1]+\beta_{2} \bar{F}\left(\bar{z}_{k}\right)[2]+\bar{F}\left(\bar{z}_{k}\right)[3]\right)\left(\beta_{1} \bar{z}_{k+\frac{1}{2}}[1]+\beta_{2} \bar{z}_{k+\frac{1}{2}}[2]+\bar{z}_{k+\frac{1}{2}}[3]\right) \leq 0,  \tag{91}\\
& \bar{z}_{k}[1]\left(\bar{z}_{k}[1]-\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)[1]\right) \leq 0,  \tag{92}\\
&-\eta \bar{F}\left(\bar{z}_{k+1}\right)[1] \mathbb{1}\left[\bar{F}\left(\bar{z}_{k+1}\right)[1] \leq 0\right]\left(\bar{z}_{k}[1]-\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)[1]\right) \leq 0 . \tag{93}
\end{align*}
$$

Equation (88) and Equation (89) follow from the combination of the fact that $\left\langle(1,-\alpha, 0, \cdots, 0), \bar{a}_{k+\frac{1}{2}}\right\rangle=0$ and that $\bar{a}_{k+\frac{1}{2}}$ and $\bar{z}_{k+\frac{1}{2}}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k}\right)$ are co-directed:

$$
\begin{aligned}
& \left\langle(1,-\alpha, 0, \cdots, 0), \bar{z}_{k+\frac{1}{2}}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k}\right)\right\rangle=0 \\
\Leftrightarrow & \left(\bar{z}_{k+\frac{1}{2}}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k}\right)\right)[1]-\alpha\left(\bar{z}_{k+\frac{1}{2}}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k}\right)\right)[2]=0 .
\end{aligned}
$$

Note that the LHS of Inequality (90) is equal to $\left\langle\bar{a}_{k+\frac{1}{2}}, \bar{z}_{k}-\eta \bar{F}\left(\bar{z}_{k}\right)\right\rangle \cdot\left\langle\bar{a}_{k+\frac{1}{2}}, \bar{z}_{k+1}\right\rangle$. Lemma 13 guarantees that $\left\langle\bar{a}_{k+\frac{1}{2}}, \bar{z}_{k+1}\right\rangle \geq 0$. Since $\bar{a}_{k+\frac{1}{2}}$ and $\bar{z}_{k}-\eta \bar{F}\left(\bar{z}_{k}\right)-\bar{z}_{k+\frac{1}{2}}$ are oppositely directed, and $\left\langle\bar{a}_{k+\frac{1}{2}}, \bar{z}_{k+\frac{1}{2}}\right\rangle=0$, we have that

$$
0 \geq\left\langle\bar{a}_{k+\frac{1}{2}}, \bar{z}_{k}-\eta \bar{F}\left(\bar{z}_{k}\right)-\bar{z}_{k+\frac{1}{2}}\right\rangle=\left\langle\bar{a}_{k+\frac{1}{2}}, \bar{z}_{k}-\eta \bar{F}\left(\bar{z}_{k}\right)\right\rangle .
$$

Hence, $\left\langle\bar{a}_{k+\frac{1}{2}}, \bar{z}_{k}-\eta \bar{F}\left(\bar{z}_{k}\right)\right\rangle \cdot\left\langle\bar{a}_{k+\frac{1}{2}}, \bar{z}_{k+1}\right\rangle \leq 0$.
Observe that the LHS of Inequality (91) is equal to $-\eta\left\langle\bar{a}_{k}, \bar{F}\left(\bar{z}_{k}\right)\right\rangle \cdot\left\langle\bar{a}_{k}, \bar{z}_{k+\frac{1}{2}}\right\rangle$. Lemma 13 guarantees that $\left\langle\bar{a}_{k}, \bar{F}\left(\bar{z}_{k}\right)\right\rangle \geq 0$ and $\left\langle\bar{a}_{k}, \bar{z}_{k+\frac{1}{2}}\right\rangle \geq 0$.

Finally, we argue Inequality (92) and Inequality (93). Note that the LHS of Inequality (92) is equal to $\left\langle\bar{a}_{k+1}, \bar{z}_{k}\right\rangle \cdot\left\langle\bar{a}_{k+1}, \bar{z}_{k}-\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)\right\rangle$. Since $\bar{a}_{k+1}$ and $\bar{z}_{k}-\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)-\bar{z}_{k+1}$ are oppositely directed, and $\left\langle\bar{a}_{k+1}, \bar{z}_{k+1}\right\rangle=0$, we have that

$$
0 \geq\left\langle\bar{a}_{k+1}, \bar{z}_{k}-\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)-\bar{z}_{k+1}\right\rangle=\left\langle\bar{a}_{k+1}, \bar{z}_{k}-\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)\right\rangle .
$$

Clearly, $-\bar{F}\left(\bar{z}_{k+1}\right) \mathbb{1}\left[\bar{F}\left(\bar{z}_{k+1}\right)[1] \leq 0\right]$ is non-negative and $\bar{z}_{k}[1]=\left\langle\bar{a}_{k+1}, \bar{z}_{k}\right\rangle$ is also non-negative due to Lemma 13. Thus Inequality (92) and Inequality (93) hold.

Our next step is to show that the following is non-negative.
Expression (87) $+2 \times$ (LHS of Equation (88) + LHS of Inequality (92) + LHS of Inequality (93))
$+\frac{2 \alpha}{1+\alpha^{2}} \times$ LHS of Equation (89) $+\frac{2}{1+\alpha^{2}} \times$ LHS of Inequality (90) $+\frac{2}{1+\beta_{1}^{2}+\beta_{2}^{2}} \times$ LHS of Inequality (91)

We first simplify Expression (94), using the following relationship between the variables.

$$
\begin{align*}
\bar{z}_{k}[3] & =-\beta_{1} \bar{z}_{k}[1]-\beta_{2} \bar{z}_{k}[2],  \tag{95}\\
\bar{z}_{k+\frac{1}{2}}[2] & =-\alpha \bar{z}_{k+\frac{1}{2}}[1],  \tag{96}\\
\bar{z}_{k+\frac{1}{2}}[3] & =\bar{z}_{k}[3]-\eta \bar{F}\left(\bar{z}_{k}\right)[3],  \tag{97}\\
\bar{z}_{k+1}[1] & =0,  \tag{98}\\
\bar{z}_{k+1}[2] & =\bar{z}_{k}[2]-\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)[2],  \tag{99}\\
\bar{z}_{k+1}[3] & =\bar{z}_{k}[3]-\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)[3] . \tag{100}
\end{align*}
$$

Equation (95), Equation (96), and Equation (98) follows by $\left\langle\bar{a}_{i}, \bar{z}_{i}\right\rangle=0$ for $i \in\left\{k, k+\frac{1}{2}, k+1\right\}$ due to Lemma 13. We know that (i) $\left\langle\bar{a}_{k+\frac{1}{2}}, e_{3}\right\rangle=\left\langle\bar{a}_{k+1}, e_{2}\right\rangle=\left\langle\bar{a}_{k+1}, e_{3}\right\rangle=0$ by the definition of $\bar{a}_{k+\frac{1}{2}}$ and $\bar{a}_{k+1}$, and (ii) $\bar{a}_{k+\frac{1}{2}}$ and $\bar{z}_{k+\frac{1}{2}}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k}\right)$ are co-directed, $\bar{a}_{k+1}$ and $\bar{z}_{k+1}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)$ are co-directed by Lemma 13, thus Equation (97), Equation (99), and Equation (100) follow from the combination of (i) and (ii).

We simplify Expression (94) by substituting $\bar{z}_{k}[3], \bar{z}_{k+\frac{1}{2}}[2], \bar{z}_{k+\frac{1}{2}}[3], \bar{z}_{k+1}[1], \bar{z}_{k+1}[2]$, and $\bar{z}_{k+1}[3]$ using Equations (95)-(100).

Expression (87) is equal to the sum of the following three parts.
The first part is

$$
\begin{align*}
& \eta^{2}\left\|p_{1}\left(\bar{F}\left(\bar{z}_{k}\right)\right)\right\|^{2}-\eta^{2}\left\|p_{1}\left(\bar{F}\left(\bar{z}_{k+1}\right)\right)\right\|^{2}-\frac{\eta^{2}}{\beta_{1}^{2}+\beta_{2}^{2}+1}\left(\beta_{1} \bar{F}\left(\bar{z}_{k}\right)[1]+\beta_{2} \bar{F}\left(\bar{z}_{k}\right)[2]+\bar{F}\left(\bar{z}_{k}\right)[3]\right)^{2} \\
& \quad+\eta^{2} \bar{F}\left(\bar{z}_{k+1}\right)[1]^{2} \mathbb{\mathbb { 1 }}\left[\bar{F}\left(\bar{z}_{k+1}\right)[1] \geq 0\right] \\
& = \\
& \sum_{i=1}^{3}\left(\eta^{2} \bar{F}\left(\bar{z}_{k}\right)[i]^{2}-\eta^{2} \bar{F}\left(\bar{z}_{k+1}\right)[i]^{2}\right)-\frac{\eta^{2}}{\beta_{1}^{2}+\beta_{2}^{2}+1}\left(\beta_{1} \bar{F}\left(\bar{z}_{k}\right)[1]+\beta_{2} \bar{F}\left(\bar{z}_{k}\right)[2]+\bar{F}\left(\bar{z}_{k}\right)[3]\right)^{2}  \tag{101}\\
& \quad+\eta^{2} \bar{F}\left(\bar{z}_{k+1}\right)[1]^{2} \mathbb{\mathbb { F }}\left[\bar{F}\left(\bar{z}_{k+1}\right)[1] \geq 0\right] .
\end{align*}
$$

The second part is

$$
\begin{align*}
& 2 \eta\left\langle p_{1}\left(\bar{F}\left(\bar{z}_{k+1}\right)\right)-p_{1}\left(\bar{F}\left(\bar{z}_{k}\right)\right), p_{1}\left(\bar{z}_{k}\right)-p_{1}\left(\bar{z}_{k+1}\right)\right\rangle \\
& =2 \eta \bar{z}_{k}[1]\left(\bar{F}\left(\bar{z}_{k+1}\right)[1]-\bar{F}\left(\bar{z}_{k}\right)[1]\right)+2 \eta^{2} \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)[2]\left(\bar{F}\left(\bar{z}_{k+1}\right)[2]-\bar{F}\left(\bar{z}_{k}\right)[2]\right) \\
& \quad+2 \eta^{2} \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)[3]\left(\bar{F}\left(\bar{z}_{k+1}\right)[3]-\bar{F}\left(\bar{z}_{k}\right)[3]\right) . \tag{102}
\end{align*}
$$

The third part is

$$
\begin{align*}
& \eta^{2}\left\|p_{1}\left(\bar{F}\left(\bar{z}_{k+1}\right)\right)-p_{1}\left(\bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)\right)\right\|^{2}-\left\|p_{1}\left(\bar{z}_{k+1}\right)-p_{1}\left(\bar{z}_{k+\frac{1}{2}}\right)\right\|^{2} \\
& =\sum_{i=1}^{3} \eta^{2}\left(\bar{F}\left(\bar{z}_{k+1}\right)[i]-\bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)[i]\right)^{2}-\bar{z}_{k+\frac{1}{2}}[1]^{2}-\left(\bar{z}_{k}[2]-\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)[2]+\alpha \bar{z}_{k+\frac{1}{2}}[1]\right)^{2} \\
& \quad-\left(\eta \bar{F}\left(\bar{z}_{k}\right)[3]-\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)[3]\right)^{2} . \tag{103}
\end{align*}
$$

$2 \times$ LHS of Equation (88) is equal to

$$
\begin{align*}
& 2 \bar{z}_{k+\frac{1}{2}}[1]\left(\left(\bar{z}_{k+\frac{1}{2}}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k}\right)\right)[1]-\alpha\left(\bar{z}_{k+\frac{1}{2}}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k}\right)\right)[2]\right) \\
& =2 \bar{z}_{k+\frac{1}{2}}[1]\left(\left(\bar{z}_{k+\frac{1}{2}}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k}\right)\right)[1]-\alpha\left(-\alpha \bar{z}_{k+\frac{1}{2}}[1]-\bar{z}_{k}[2]+\eta \bar{F}\left(\bar{z}_{k}\right)[2]\right)\right) . \tag{104}
\end{align*}
$$

$\frac{2 \alpha}{1+\alpha^{2}} \times$ LHS of Equation (89) is equal to

$$
\begin{align*}
& \frac{2 \alpha}{1+\alpha^{2}} \bar{z}_{k+1}[2]\left(\left(\bar{z}_{k+\frac{1}{2}}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k}\right)\right)[1]-\alpha\left(\bar{z}_{k+\frac{1}{2}}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k}\right)\right)[2]\right) \\
& =\frac{2 \alpha}{1+\alpha^{2}}\left(\bar{z}_{k}[2]-\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)[2]\right)\left(\left(\bar{z}_{k+\frac{1}{2}}-\bar{z}_{k}+\eta \bar{F}\left(\bar{z}_{k}\right)\right)[1]-\alpha\left(-\alpha \bar{z}_{k+\frac{1}{2}}[1]-\bar{z}_{k}[2]+\eta \bar{F}\left(\bar{z}_{k}\right)[2]\right)\right) . \tag{105}
\end{align*}
$$

$\frac{2}{1+\alpha^{2}} \times$ LHS of Inequality (90) is equal to

$$
\begin{align*}
& \frac{2}{1+\alpha^{2}}\left(\alpha\left(\bar{z}_{k}-\eta \bar{F}\left(\bar{z}_{k}\right)\right)[1]+\left(\bar{z}_{k}-\eta \bar{F}\left(\bar{z}_{k}\right)\right)[2]\right)\left(\alpha \bar{z}_{k+1}[1]+\bar{z}_{k+1}[2]\right) \\
& =\frac{2}{1+\alpha^{2}}\left(\alpha\left(\bar{z}_{k}-\eta \bar{F}\left(\bar{z}_{k}\right)\right)[1]+\left(\bar{z}_{k}-\eta \bar{F}\left(\bar{z}_{k}\right)\right)[2]\right)\left(\bar{z}_{k}[2]-\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}[2]\right)\right. \tag{106}
\end{align*}
$$

$\frac{2}{1+\beta_{1}^{2}+\beta_{2}^{2}} \times$ LHS of Inequality (91) is equal to

$$
\begin{align*}
& -\frac{2}{1+\beta_{1}^{2}+\beta_{2}^{2}}\left(\beta_{1} \eta \bar{F}\left(\bar{z}_{k}\right)[1]+\beta_{2} \eta \bar{F}\left(\bar{z}_{k}\right)[2]+\eta \bar{F}\left(\bar{z}_{k}\right)[3]\right)\left(\beta_{1} \bar{z}_{k+\frac{1}{2}}[1]+\beta_{2} \bar{z}_{k+\frac{1}{2}}[2]+\bar{z}_{k+\frac{1}{2}}[3]\right) \\
& =-\frac{2}{1+\beta_{1}^{2}+\beta_{2}^{2}}\left(\beta_{1} \eta \bar{F}\left(\bar{z}_{k}\right)[1]+\beta_{2} \eta \bar{F}\left(\bar{z}_{k}\right)[2]+\eta \bar{F}\left(\bar{z}_{k}\right)[3]\right)\left(\left(\beta_{1}-\alpha \beta_{2}\right) \bar{z}_{k+\frac{1}{2}}[1]+\bar{z}_{k}[3]-\eta \bar{F}\left(\bar{z}_{k}\right)[3]\right) \\
& =-\frac{2}{1+\beta_{1}^{2}+\beta_{2}^{2}}\left(\eta \beta_{1} \bar{F}\left(\bar{z}_{k}\right)[1]+\eta \beta_{2} \bar{F}\left(\bar{z}_{k}\right)[2]+\eta \bar{F}\left(\bar{z}_{k}\right)[3]\right) \\
& \quad \cdot\left(\left(\beta_{1}-\alpha \beta_{2}\right) \bar{z}_{k+\frac{1}{2}}[1]-\beta_{1} \bar{z}_{k}[1]-\beta_{2} \bar{z}_{k}[2]-\eta \bar{F}\left(\bar{z}_{k}\right)[3]\right) . \tag{107}
\end{align*}
$$

$2 \times$ LHS of Inequality (92) is equal to

$$
\begin{equation*}
2 \bar{z}_{k}[1]\left(\bar{z}_{k}[1]-\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)[1]\right) . \tag{108}
\end{equation*}
$$

$2 \times$ LHS of Inequality (93) is equal to

$$
\begin{equation*}
-2 \eta \bar{F}\left(\bar{z}_{k+1}\right)[1] \mathbb{1}\left[\bar{F}\left(\bar{z}_{k+1}\right)[1] \leq 0\right]\left(\bar{z}_{k}[1]-\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)[1]\right) . \tag{109}
\end{equation*}
$$

After the substitution, we need to argue that the sum of Expression (101) to (109) is a sum of quotients of SOS polynomials, which we prove by establishing the following identity.

Expression (101) + Expression (102) + Expression (103) + Expression (104) + Expression (105)

+ Expression (106) + Expression (107) + Expression (108) + Expression (109)
$=\left(\bar{z}_{k}[1]-\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)[1]+\eta \bar{F}\left(\bar{z}_{k+1}\right)[1] \cdot \mathbb{1}\left[\bar{F}\left(\bar{z}_{k+1}\right)[1] \geq 0\right]\right)^{2}$
$+\frac{\left(\bar{z}_{k}[1]-\eta \bar{F}\left(\bar{z}_{k}\right)[1]-\bar{z}_{k+\frac{1}{2}}[1]\right)^{2}}{1+\beta_{1}^{2}+\beta_{2}^{2}}$
$+\frac{\left(\eta \bar{F}\left(\bar{z}_{k}\right)[3]+\beta_{1} \bar{z}_{k}[1]+\beta_{2} \bar{z}_{k}[2]+\left(\alpha \beta_{2}-\beta_{1}\right) \bar{z}_{k+\frac{1}{2}}[1]\right)^{2}}{1+\beta_{1}^{2}+\beta_{2}^{2}}$
$+\frac{\left(\bar{z}_{k}[2]-\eta \bar{F}\left(\bar{z}_{k}\right)[2]+\alpha \bar{z}_{k+\frac{1}{2}}[1]\right)^{2}}{1+\beta_{1}^{2}+\beta_{2}^{2}}$
$+\frac{\left(\beta_{1}\left(\bar{z}_{k}[2]-\eta \bar{F}\left(\bar{z}_{k}\right)[2]+\alpha \bar{z}_{k+\frac{1}{2}}[1]\right)-\beta_{2}\left(\bar{z}_{k}[1]-\eta \bar{F}\left(\bar{z}_{k}\right)[1]-\bar{z}_{k+\frac{1}{2}}[1]\right)\right)^{2}}{1+\beta_{1}^{2}+\beta_{2}^{2}}$
$\geq 0$.
The identity for the case where $\bar{F}\left(\bar{z}_{k+1}\right)[1] \geq 0$ is verified at Appendix $F$ in the second version of this paper on arXiv, which can be found at this link. Observe that only Expression (101), Expression (109) and Term (110) depend on the sign of $\bar{F}\left(\bar{z}_{k+1}\right)[1]$. It is sufficient for us to verify the case where $\bar{F}\left(\bar{z}_{k+1}\right)[1] \geq 0$, as when $\bar{F}\left(\bar{z}_{k+1}\right)[1]<0$, we only need to subtract $\eta^{2} \bar{F}\left(\bar{z}_{k+1}\right)[1]^{2}+2 \eta \bar{F}\left(\bar{z}_{k+1}\right)[1]\left(\bar{z}_{k}[1]-\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)[1]\right)$ from both the LHS and the RHS, ${ }^{16}$ and the identity still holds.

Hence, Expression (87) is non-negative. Combining with the non-negativity of Expression (86), we conclude that TARGET is non-negative. This completes the proof.

[^16]
[^0]:    *Supported by a Sloan Foundation Research Fellowship and the NSF Award CCF-1942583 (CAREER).
    ${ }^{\dagger}$ Part of this work was done while the author was visiting the Simons Institute for the Theory of Computing.

[^1]:    ${ }^{1} F$ is monotone if $\left\langle F(z)-F\left(z^{\prime}\right), z-z^{\prime}\right\rangle \geq 0$ for all $z, z^{\prime} \in \mathcal{Z}$.
    ${ }^{2}$ If we set $F(x, y)=\binom{\nabla_{x} f(x, y)}{-\nabla_{y} f(x, y)}$ and $\mathcal{Z}=\mathcal{X} \times \mathcal{Y}$, then (i) $F(x, y)$ is a monotone and Lipschitz operator, and (ii)
    the set of saddle points coincide with the solutions of the monotone VI for operator $F$ and domain $\mathcal{Z}$.
    ${ }^{3}$ The last-iterate asymptotic convergence of EG can be found in Korpelevich [1976] and Facchinei and Pang [2007], and the last-iterate asymptotic convergence of OGDA can be found in Popov [1980] and Hsieh et al. [2019].

[^2]:    ${ }^{a}$ In the unconstrained setting, the tangent residual is simply the $\ell_{2}$-norm of $F$. In the constrained setting, the tangent residual is the $\ell_{2}$-norm of $F^{\prime}$ s projection to the tangent cone.

[^3]:    ${ }^{4}$ A two-player zero-sum game can be specified by its payoff matrix $A \in \mathbb{R}^{\ell \times m}$. It is a special case of the convexconcave saddle point problem, where $\mathcal{X}=\Delta^{\ell}, \mathcal{Y}=\Delta^{m}$ ( $\Delta^{k}$ denotes the $k$-dimensional simplex), and the function $f(x, y)=x^{\top} A y$.

[^4]:    ${ }^{5}$ The tangent residual is not a polynomial, but the squared tangent residual is a degree-4 polynomial

[^5]:    ${ }^{6}$ More specifically, the PEP framework requires the performance measure as well as the constraints to be linear in (i) the function values at the iterates and (ii) the Gram matrix of a set of vectors consisting of the iterates and their gradients.
    ${ }^{7}$ The tangent residual is the square root of a rational function and can only be even harder to handle.

[^6]:    ${ }^{8}$ Sometimes the gap function is defined to allow $z^{\prime}$ to take value in $\mathcal{Z} \cap \mathcal{B}\left(z^{*},\left\|z^{*}-z_{0}\right\|\right)$, where $z_{0}$ is the starting point of the EG algorithm, and $z^{*}$ is the solution that the last iterate of the algorithm converges to. Due to Lemma 3, $\left\|z_{k}-z^{*}\right\| \leq\left\|z_{0}-z^{*}\right\|$ for every $k$, so $\mathcal{B}\left(z_{k}, 2\left\|z^{*}-z_{0}\right\|\right)$ contains $\mathcal{B}\left(z^{*},\left\|z^{*}-z_{0}\right\|\right)$.

[^7]:    ${ }^{9}\left\|z_{k}-z_{k+1 / 2}\right\|$ is proportional to the norm of the operator mapping introduced in [Diakonikolas, 2020].

[^8]:    ${ }^{10}$ When $\mathcal{X}$ and $\mathcal{Y}$ are bounded, we choose $\mathcal{X}^{\prime}=\mathcal{X}$ and $\mathcal{Y}^{\prime}=Y$, otherwise the convention is to choose $\mathcal{X}^{\prime}$ and $\mathcal{Y}^{\prime}$ to be $\mathcal{X} \cap \mathcal{B}\left(x^{*}, 2\left\|x_{0}-x^{*}\right\|\right)$ and $\mathcal{Y} \cap \mathcal{B}\left(y^{*}, 2\left\|y_{0}-y^{*}\right\|\right)$ respectively, where $\left(x^{*}, y^{*}\right)$ is a saddle point.

[^9]:    ${ }^{11}$ In the unconstrained setting, the tangent residual is simply the norm of the operator $r_{\left(F, \mathbb{R}^{n}\right)}^{t a n}(z)=\|F(z)\|$.

[^10]:    ${ }^{12}$ Simply replace $\left\{z_{i}[\ell]\right\}_{i \in K}$ and $\left\{\eta F\left(z_{i}\right)[\ell]\right\}_{i \in K}$ with $\left\{z_{i}\left[\ell^{\prime}\right]\right\}_{i \in K}$ and $\left\{\eta F\left(z_{i}\right)\left[\ell^{\prime}\right]\right\}_{i \in K}$.

[^11]:    ${ }^{a} C$ represents $(\eta L)^{2}$. Larger $C$ corresponds to a larger step size and makes the SOS program harder to satisfy. Through binary search, we find that the largest possible value of $C$ is 1 while maintaining the feasibility of the SOS program.

[^12]:    ${ }^{13}$ We mainly care about the polynomials arise from the constraints. Although $\gamma_{1}^{(\ell)}(\boldsymbol{w})$ and $\gamma_{2}^{(\ell)}(\boldsymbol{w})$ could depend on other coordinates, we show that it suffices to consider polynomials in $\left\{z_{i}[\ell], \eta F\left(z_{i}\right)[\ell]\right\}_{i \in K}$.

[^13]:    ${ }^{a} C$ represents $(\eta L)^{2}$.

[^14]:    ${ }^{14}$ To avoid finding the trivial linear combination, i.e., all coefficients equal to 0 , we also use the objective function in the SOS program to encourage a non-trivial solution if one exists by, for example, maximizing the sum of the coefficients of the linear combination.

[^15]:    ${ }^{15}$ This is because $\left\langle\widehat{F}\left(\hat{z}_{k+1}\right), \hat{a}_{k+1}\right\rangle$ is never smaller than $\left\langle F\left(z_{k+1}\right), a_{k+1}\right\rangle$, and the function $\mathbb{1}[x \geq 0]$ is right continuous.

[^16]:    ${ }^{16}$ Notice that $\left(\bar{z}_{k}[1]-\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)[1]+\eta \bar{F}\left(\bar{z}_{k+1}\right)[1]\right)^{2} \quad=\quad\left(\bar{z}_{k}[1]-\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)[1]\right)^{2}+\eta^{2} \bar{F}\left(\bar{z}_{k+1}\right)[1]^{2}+$ $2 \eta \bar{F}\left(\bar{z}_{k+1}\right)[1]\left(\bar{z}_{k}[1]-\eta \bar{F}\left(\bar{z}_{k+\frac{1}{2}}\right)[1]\right)$.

