

A SMOOTH PENALTY APPROACH AND A NONLINEAR MULTIGRID ALGORITHM FOR ELLIPTIC MPECS

M. HINTERMÜLLER AND I. KOPACKA

ABSTRACT. An optimal control problem governed by an elliptic variational inequality of the first kind and bilateral control constraints is studied. A smooth penalization technique for the variational inequality is applied and convergence of stationary points of the subproblems to an \mathcal{E} -almost C-stationary point of the limit problem is shown. The subproblems are solved using a full approximation multigrid scheme (FAS) and alternatively a multigrid method of the second kind for which a convergence result is given. An overall algorithmic concept is provided and its performance is discussed by means of examples.

1. INTRODUCTION AND PROBLEM FORMULATION

In this paper we study a new stationarity concept and multigrid algorithms for the following minimization problem (\mathcal{P}):

$$(1.1a) \quad \min J(y, u) = \frac{1}{2} \|y - y_d\|_{L^2}^2 + \frac{\nu}{2} \|u\|_{L^2}^2 \quad \text{over } y \in V, u \in L^2(\Omega)$$

$$(1.1b) \quad \begin{aligned} &\text{s.t. (subject to) } y \in K, a(y, v - y) \geq (f + u, v - y) \quad \forall v \in K, \\ &a \leq u \leq b \text{ a.e. in } \Omega. \end{aligned}$$

where $\Omega \subset \mathbb{R}^n$, $n \leq 3$, is an open, bounded domain with a smooth boundary $\partial\Omega$ and $a(\cdot, \cdot) : V \times V \rightarrow \mathbb{R}$, with $V = H_0^1(\Omega)$, denotes the bilinear form

$$a(v, w) = \sum_{i,j=1}^n \int_{\Omega} a_{ij} \frac{\partial v}{\partial x_j} \frac{\partial w}{\partial x_i} dx + \sum_{i=1}^n \int_{\Omega} b_i \frac{\partial v}{\partial x_i} w dx + \int_{\Omega} c v w dx,$$

for all $v, w \in V$, where $b_i, c \in L^\infty(\Omega)$, $a_{ij} \in C^{0,1}(\bar{\Omega})$ and $c \geq 0$. Further let $a(\cdot, \cdot)$ be bounded and coercive, i.e., there exist constants $C_B, C_C > 0$ such that for all $v, w \in V$

$$(1.2) \quad |a(v, w)| \leq C_B \|v\|_V \|w\|_V \quad \wedge \quad a(v, v) \geq C_C \|v\|_V^2.$$

The variational inequality (VI) constraint (1.1a) involves the cone $K = \{v \in V : v \geq 0 \text{ a.e. in } \Omega\}$. By (\cdot, \cdot) and $\|\cdot\|$ we denote the scalar product and norm, respectively, in $L^2(\Omega)$ and by $\langle \cdot, \cdot \rangle$ the duality pairing between V and $V^* = H^{-1}(\Omega)$. Moreover, $y_d, f \in L^2$ are given, $\nu > 0$ is fixed, and the bounds on the control variable u are $a, b \in L^2(\Omega) \cup \{-\infty, \infty\}$ with $(b - a) > 0$. The state variable is denoted by y . Note that our notation allows us to choose $a \equiv -\infty$, $b \equiv \infty$ if no lower or upper bound acts on the control.

Date: November 19, 2008.

2000 Mathematics Subject Classification. 35J20, 49K20, 65K10, 65N55, 90C33, 90C46.

Key words and phrases. Constrained optimal control, elliptic variational inequality, MPEC, mathematical programs with complementarity constraints, C-stationarity, nonlinear multigrid.

The authors gratefully acknowledge support by the Austrian Federal Ministry of Science and Research (bmw_f) and the FWF under START-program Y305 "Interfaces and Free Boundaries".

We recall that, given $u \in L^2(\Omega)$, the variational inequality (1.1a) admits a unique solution $y \in V$. If $u + f \in L^2(\Omega)$ and Ω is sufficiently regular, then $y \in H^2(\Omega) \cap V$; see, for instance, [13, 24]. In [26] it was proven that (\mathcal{P}) admits a solution.

Our model problem (\mathcal{P}) is a particular instance of a mathematical program with equilibrium constraints (MPEC) in function space. Problems of this type were considered earlier in [1, 2, 3, 4, 5, 6, 20, 26, 27] and the references therein. In these papers typically versions of first order conditions are derived. Let us point out that due to the VI constraint classical constraint qualifications [33] are generically violated by (\mathcal{P}) . Hence, alternative proof concepts for deriving stationarity conditions need to be developed. In the aforementioned papers and monographs mainly two approaches are used: relaxation of a primal-dual form of the VI constraint ([2]) and regularized penalization ([1, 20, 26], for instance). In [23], as in [2], a relaxation approach was pursued in order to categorize first order conditions similar to finite dimensions [25, 28, 29, 32]. Depending on the realization of the VI constraint and the induced regularity of associated Lagrange multipliers, new versions of stationarity arise in function space; see, e.g., " \mathcal{E} -almost C-stationarity" (Definition 3.2) and "almost C-stationarity", concepts which were introduced in [23]. We point out that in finite dimensional space these notions coincide with C-stationarity.

The literature on solution algorithms for (\mathcal{P}) is relatively scarce. In [2] a multiplier method is used but only for the relaxed problems without driving the relaxation parameter to zero. The approach in [20] is based on a nonlinear complementarity (NCP) function based reformulation of the VI constraint and a subsequent least-squares approach to a first order system establishing weak stationarity. Then, in [21] an active-set Newton solver is proposed for obtaining some type of C-stationary points which may be interpreted as a particular version of an implicit programming approach to MPECs; see [28] for the latter. Further, as the proof technique in [23] is constructive an associated solution algorithm is proposed in [23] based on a relaxation scheme and a path-following semismooth Newton solver.

While the relaxation approach of [23] is rather general and allows to derive stronger first order conditions, the regularized penalty approach may preserve certain structures, which might be advantageous in the design of algorithms. For instance, (\mathcal{P}) admits an interpretation as a bilevel optimization problem in function space due to the fact that the VI constraint represents the first order necessary and sufficient condition of state lower level minimization problem.

The penalty approach which we will use in this paper preserves this structure, i.e., after penalizing and smoothing the VI constraint the overall problem still admits a bilevel structure. In addition, the resulting minimization problem resembles an optimal control problem for a semilinear elliptic partial differential equation with point-wise constraints on the control. Based on [8, 7, 10, 16, 17, 19], in this paper we introduce multigrid solvers for these problems. In fact, we study the full approximation scheme (FAS) [7, 10] and a multigrid method of the second kind [17] and embed these methods in a continuation scheme for the penalty and/or smoothing parameter. Under a non-degeneracy condition, we establish a convergence result for the version based on the multigrid method of the second kind. To the best of our knowledge these are the first multigrid-based solvers for MPECs in function space.

The rest of the paper is organized as follows. In the next section we introduce our smoothed penalty approach and study some of its properties. Then we derive first

order optimality conditions in section 3. Here we focus on the concept of \mathcal{E} -almost C-stationarity. Section 4 introduces first a FAS-scheme and then a nonlinear multigrid method of the second kind for solving the penalized and smoothed problems. For the latter approach a convergence result is given. The paper ends by a report on numerical tests comparing both variants of multigrid solvers and different types of penalization.

2. PENALIZATION OF THE VARIATIONAL INEQUALITY

A common technique for solving a variational inequality of the form (1.1a) is by penalization (see, e.g., [14, 24]). Using this technique the variational inequality is approximated by a series of nonlinear boundary value problems. For a given penalty operator $\pi : V \rightarrow V^*$ with the following properties:

$$(2.1) \quad \begin{cases} \pi \text{ is Lipschitz continuous,} \\ Ker(\pi) = K, \\ \pi \text{ is monotone,} \end{cases}$$

the VI can be approximated by the penalized equation

$$(2.2) \quad a(y, v) + \frac{1}{\alpha} \langle \pi(y), v \rangle = (f + u, v) \quad \forall v \in V,$$

with $\alpha > 0$ being the *penalty parameter*. Due to the monotonicity of the nonlinear operator π , equation (2.2) has a unique solution (see, e.g., [14]) which we denote by $y_\alpha(u)$. Furthermore if we denote the solution of (1.1a) by $y(u)$, it is well known that

$$(2.3) \quad y_\alpha(u) \rightarrow y(u) \text{ in } V \text{ as } \alpha \downarrow 0,$$

(see, e.g., [14]). In this paper we consider the penalty operator

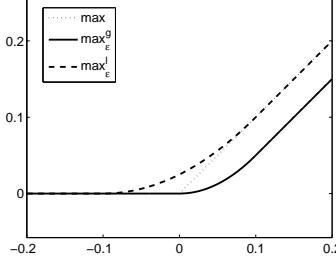
$$\pi(v) := -\max(0, -v) \quad \forall v \in V,$$

where the max-operation is to be understood point-wise. As the $\max(0, \cdot)$ -function is not differentiable at the origin we introduce different regularizations yielding C^1 -approximations of $\max(0, \cdot)$. For a fixed *smoothing parameter* $\varepsilon > 0$ we define the following regularized/smoothed operators:

$$(2.4) \quad \max_\varepsilon^g(0, r) := \begin{cases} r - \frac{\varepsilon}{2} & \text{if } r \geq \varepsilon \\ \frac{r^2}{2\varepsilon} & \text{if } r \in (0, \varepsilon), \\ 0 & \text{if } r \leq 0 \end{cases} \quad \max_\varepsilon^l(0, r) := \begin{cases} r & \text{if } r \geq \varepsilon \\ \frac{r^2}{4\varepsilon} + \frac{r}{2} + \frac{\varepsilon}{4} & \text{if } r \in (-\varepsilon, \varepsilon), \\ 0 & \text{if } r \leq -\varepsilon \end{cases}$$

Both regularizations are C^1 -functions that smooth the kink of the max-operator. As illustrated in Figure 2.1 the regularization \max_ε^l alters the function locally around the origin but leaves the operator unchanged outside of this neighborhood, whereas the smoothing of \max_ε^g affects the operator on the whole half-plane. We will therefore refer to the two operators as "local" and "global" regularizations, respectively. In the context of penalization we note that the global regularization itself defines a suitable penalty operator for the variational inequality, i.e., it satisfies (2.1), while the local regularization \max_ε^l violates the second condition of (2.1) for every $\varepsilon > 0$.

In the following lemma useful properties of these operators are provided. We also state some of the differences between the regularizations.

FIGURE 2.1. $\max(0, \cdot)$ and regularizations \max_ε^g and \max_ε^l .**Lemma 2.1.**

- (i) Both \max_ε^g and \max_ε^l are monotone and convex.
- (ii) The global variant \max_ε^g penalizes the set K , i.e., $\max_\varepsilon^g(0, -\cdot)$ satisfies conditions (2.1). The local variant \max_ε^l is not a suitable penalty operator for K . The violation of (2.1) can be estimated by:

$$\|\max_\varepsilon^l(0, -v)\|_{L^2} \leq \frac{\varepsilon}{4} \sqrt{\text{meas}(\Omega)} \quad \forall v \in K.$$

Furthermore if $\max_\varepsilon^l(0, -v) = 0$ then $v \in K$.

- (iii) We have $(\max_\varepsilon^g(0, -v), v) \leq 0$ for all $v \in L^2(\Omega)$ and the local variant satisfies

$$(\max_\varepsilon^l(0, -v), v) \leq \frac{\varepsilon^2}{4} \text{meas}(\Omega) \quad \forall v \in L^2(\Omega).$$

- (iv) For all $r \in \mathbb{R}$ we find that

$$\begin{aligned} 0 &\leq \max(0, r) - \max_\varepsilon^g(0, r) \leq \frac{\varepsilon}{2}, \\ 0 &\leq \max_\varepsilon^l(0, r) - \max(0, r) \leq \frac{\varepsilon}{4}. \end{aligned}$$

- (v) Both $(\max_\varepsilon^g(0, r))'$ and $(\max_\varepsilon^l(0, r))' \in [0, 1]$ for all $r \in \mathbb{R}$. As a consequence both regularizations are Lipschitz continuous with Lipschitz constant 1.
- (vi) The global regularization has a Lipschitz property with respect to ε , i.e.,

$$|\max_{\varepsilon_1}^g(0, r) - \max_{\varepsilon_2}^g(0, r)| \leq \frac{3}{2} |\varepsilon_1 - \varepsilon_2|$$

for all $r \in \mathbb{R}$ and $\varepsilon_1, \varepsilon_2 > 0$.

Proof. Assertions (i), (iv) and (v) are evident. For the estimate in (ii) assume that $v \geq 0$ a.e. in Ω . Then

$$\|\max_\varepsilon^l(0, -v)\|_{L^2}^2 = \int_{\{-\varepsilon < -v \leq 0\}} \max_\varepsilon^l(0, -v)^2 \leq \left(\frac{\varepsilon}{4}\right)^2 \int_{\{-\varepsilon < -v \leq 0\}} 1 \leq \left(\frac{\varepsilon}{4}\right)^2 \text{meas}(\Omega),$$

as $0 \leq \max_\varepsilon^l(0, r) \leq \frac{\varepsilon}{4}$ for all $-\varepsilon \leq r \leq 0$. The proof of the estimate for \max_ε^l in (iii) is done analogously. In order to prove (vi) w.l.o.g. let $\varepsilon_1 < \varepsilon_2$ and $r \in \mathbb{R}$. We investigate several cases. If $r \leq 0$ then $\max_{\varepsilon_1}^g(0, r) - \max_{\varepsilon_2}^g(0, r) = 0$. If $0 < r < \varepsilon_1$

then

$$|\max_{\varepsilon_1}^g(0, r) - \max_{\varepsilon_2}^g(0, r)| = \frac{r^2}{2} \left(\frac{1}{\varepsilon_1} - \frac{1}{\varepsilon_2} \right) = \frac{r^2}{2} \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_1 \varepsilon_2} \leq \frac{1}{2} (\varepsilon_2 - \varepsilon_1).$$

If $\varepsilon_1 \leq r < \varepsilon_2$ then

$$\begin{aligned} |\max_{\varepsilon_1}^g(0, r) - \max_{\varepsilon_2}^g(0, r)| &= r - \frac{\varepsilon_1}{2} - \frac{1}{2\varepsilon_2} r^2 \leq \varepsilon_2 - \frac{\varepsilon_1}{2} - \frac{\varepsilon_1^2}{2\varepsilon_2} \\ &= \frac{\varepsilon_2}{2} - \frac{\varepsilon_1}{2} + \frac{\varepsilon_2^2}{2\varepsilon_2} - \frac{\varepsilon_1^2}{2\varepsilon_2} = \frac{1}{2} \left(1 + \frac{\varepsilon_2 + \varepsilon_1}{\varepsilon_2} \right) (\varepsilon_2 - \varepsilon_1) \\ &\leq \frac{3}{2} (\varepsilon_2 - \varepsilon_1). \end{aligned}$$

Finally if $\varepsilon_2 \leq r$ then

$$|\max_{\varepsilon_1}^g(0, r) - \max_{\varepsilon_2}^g(0, r)| = r - \frac{\varepsilon_1}{2} - \left(r - \frac{\varepsilon_2}{2} \right) = \frac{1}{2} (\varepsilon_2 - \varepsilon_1).$$

□

As we shall see in Section 4.1.2 sometimes it is of interest to consider even smoother regularizations. Here we introduce a C^2 -regularization, which, for the sake of simplicity, is presented in its "global" form only.

$$(2.5) \quad \max_{\varepsilon}^G(0, r) := \begin{cases} r - \frac{\varepsilon}{2} & \text{if } r \geq \varepsilon, \\ \frac{r^3}{\varepsilon^2} - \frac{r^4}{2\varepsilon^3} & \text{if } r \in (0, \varepsilon), \\ 0 & \text{if } r \leq 0. \end{cases}$$

Remark 2.2. The results of Lemma 2.1 remain true if \max_{ε}^g is replaced by \max_{ε}^G and the Lipschitz constant in (vi) is replaced by 7/2.

Due to the non-smoothness of the $\max(0, \cdot)$ -operator we are interested in a result similar to (2.3) but using the smoothed operators. As noted earlier the global regularization satisfies the penalization properties whereas the local regularization violates (2.1) for all $\varepsilon > 0$. This is reflected in the fact that the smoothing parameter ε has to be driven to zero in order to achieve convergence if the local regularization is used, while the global regularization permits the choice of a fixed positive smoothing parameter. We therefore make the following assumption on the smoothing parameter.

Assumption 2.1. For each $\alpha > 0$ let $\varepsilon(\alpha) > 0$ be given such that

- (i) $\{\varepsilon(\alpha)\}$ is bounded if \max_{ε}^g or \max_{ε}^G is used and
- (ii) $\frac{\varepsilon(\alpha)}{\alpha} \rightarrow 0$ if \max_{ε}^l is used.

The following theorem describes the approximation properties of the regularized penalized equations.

Theorem 2.3. Let $\{u_{\alpha}\}$ be a sequence in $L^2(\Omega)$, $u \in L^2(\Omega)$ such that $u_{\alpha} \rightarrow u$ (strongly) in V^* . Let $\{\varepsilon(\alpha)\}$ satisfy Assumption 2.1 and $y_{\alpha} \in V$ denote the solution of the regularized penalized equation

$$(2.6) \quad \mathcal{A}y_{\alpha} - \frac{1}{\alpha} \max_{\varepsilon(\alpha)}(0, -y_{\alpha}) = u_{\alpha} + f,$$

where \max_{ε} stands for either of the regularizations introduced in the beginning of this section. Then

$$y_{\alpha} \rightarrow y(u) \text{ in } V \text{ if } \alpha \rightarrow 0,$$

where $y(u)$ denotes the solution of (1.1a).

Proof. We use similar arguments as in [14], Theorem 3.1, Chapter 1. In the course of this paper we will frequently operate on subsequences which we will, for the sake of readability, not always denote specifically.

In the first part of the proof we consider the global regularizations \max_{ε}^g and \max_{ε}^G . For the sake of simplicity we give the proof for \max_{ε}^g only, but all of our arguments apply to the C^2 -regularization. Let $v \in K$ be arbitrarily fixed. Due to the monotonicity of \max_{ε}^g and Lemma 2.1 (ii) we estimate

(2.7)

$$0 \leq \left(-\max_{\varepsilon(\alpha)}^g(0, -y_\alpha) + \max_{\varepsilon(\alpha)}^g(0, -v), y_\alpha - v \right) = -\left(\max_{\varepsilon(\alpha)}^g(0, -y_\alpha), y_\alpha - v \right).$$

Using (2.6) we then obtain

$$(2.8) \quad \langle \mathcal{A}y_\alpha, y_\alpha \rangle \leq \langle u_\alpha + f, y_\alpha - v \rangle + \langle \mathcal{A}y_\alpha, v \rangle.$$

Hence the boundedness and the coercivity of \mathcal{A} yield the boundedness of $\{y_\alpha\}$ in V . From (2.6) we infer

$$\| \max_{\varepsilon(\alpha)}^g(0, -y_\alpha) \|_{V^*} = \alpha \| \mathcal{A}y_\alpha - u_\alpha - f \|_{V^*} = \mathcal{O}(\alpha),$$

and therefore

$$(2.9) \quad \max_{\varepsilon(\alpha)}^g(0, -y_\alpha) \rightarrow 0 \text{ in } V^* \text{ if } \alpha \rightarrow 0.$$

As $\{y_\alpha\}$ is bounded, there exists $\bar{y} \in V$ such that (on a subsequence denoted the same) $y_\alpha \rightarrow \bar{y}$ weakly in V and strongly in $L^2(\Omega)$. Since $\{\varepsilon(\alpha)\}$ is a bounded sequence there exists yet another subsequence and a non-negative parameter $\bar{\varepsilon}$, such that $\varepsilon(\alpha) \rightarrow \bar{\varepsilon}$ on that subsequence. Due to the Lipschitz properties (v) and (vi) of Lemma 2.1 we find that

$$\begin{aligned} & \| \max_{\bar{\varepsilon}}^g(0, -\bar{y}) - \max_{\varepsilon(\alpha)}^g(0, -y_\alpha) \|_{V^*} \leq \\ & \leq \| \max_{\bar{\varepsilon}}^g(0, -\bar{y}) - \max_{\bar{\varepsilon}}^g(0, -y_\alpha) \|_{V^*} + \| \max_{\bar{\varepsilon}}^g(0, -y_\alpha) - \max_{\varepsilon(\alpha)}^g(0, -y_\alpha) \|_{V^*} \\ & \leq C (\| \bar{y} - y_\alpha \| + |\bar{\varepsilon} - \varepsilon(\alpha)|) \rightarrow 0. \end{aligned}$$

This, combined with (2.9), shows that $\max_{\bar{\varepsilon}}^g(0, -\bar{y}) = 0$ in V^* . Due to the density of V in $L^2(\Omega)$ we find that $\max_{\bar{\varepsilon}}^g(0, -\bar{y})$ also vanishes in $L^2(\Omega)$, hence $\bar{y} \in K$. Due to the weak convergence of y_α and the coercivity of A , taking the $\liminf_{\alpha \rightarrow 0}$ in (2.8) yields

$$\langle \mathcal{A}\bar{y}, \bar{y} \rangle \leq \langle u + f, \bar{y} - v \rangle + \langle \mathcal{A}\bar{y}, v \rangle, \quad \forall v \in K.$$

Therefore $\bar{y} = y(u)$. Due to the uniqueness of the solution of the variational inequality we conclude that in fact the whole sequence $\{y_\alpha\}$ converges (not just a subsequence). Finally the strong convergence of y_α follows from the coercivity of \mathcal{A} , (2.6) and (2.7) since

$$\begin{aligned} C_C \|y_\alpha - \bar{y}\|_V^2 & \leq \langle \mathcal{A}(y_\alpha - \bar{y}), y_\alpha - \bar{y} \rangle \\ & = \langle u_\alpha + f, y_\alpha - \bar{y} \rangle + \frac{1}{\alpha} (\max_{\varepsilon(\alpha)}^g(0, -y_\alpha), y_\alpha - \bar{y}) - \langle \mathcal{A}\bar{y}, y_\alpha - \bar{y} \rangle \\ & \leq \langle u_\alpha + f, y_\alpha - \bar{y} \rangle - \langle \mathcal{A}\bar{y}, y_\alpha - \bar{y} \rangle \rightarrow 0. \end{aligned}$$

The proof for \max_{ε}^l uses the same arguments, but replaces the estimate (2.7) with

$$0 \leq -\left(\max_{\varepsilon(\alpha)}^l(0, -y_\alpha), y_\alpha - v \right) + \frac{1}{4} \text{meas}(\Omega)^{1/2} \varepsilon(\alpha) \|y_\alpha - v\|$$

and uses $\varepsilon(\alpha)/\alpha \rightarrow 0$. \square

3. THE OPTIMAL CONTROL PROBLEM

In this paper we solve the MPEC (\mathcal{P}) by approximating the lower-level problem, i.e., the variational inequality, using the techniques developed in the previous section. For each set of parameters $(\alpha, \varepsilon) > 0$ we therefore define the smoothed penalized problem $(\mathcal{P}_{\alpha, \varepsilon})$ by

$$(3.1) \quad \begin{aligned} \min J(y, u) &= \frac{1}{2} \|y - y_d\|_{L^2}^2 + \frac{\nu}{2} \|u\|_{L^2}^2 \quad \text{over } y \in V, u \in L^2(\Omega) \\ \text{s.t. } \mathcal{A}y - \frac{1}{\alpha} \max_{\varepsilon}(0, -y) &= u + f, \\ a \leq u \leq b &\quad \text{a.e. in } \Omega, \end{aligned}$$

where \max_{ε} is a generic denotation that stands for either of the regularizations introduced in Section 2. Using arguments similar to those in [23] and considering the properties listed in Lemma 2.1 the existence of a globally optimal point for problem $(\mathcal{P}_{\alpha, \varepsilon})$ can be shown. Furthermore the following result describing the convergence behavior of globally optimal points can again be proven using the arguments of [23] and Lemma 2.1.

Theorem 3.1. *Let α and $\varepsilon(\alpha)$ be given such that Assumption 2.1 is satisfied and denote by (y_α, u_α) the global solutions of the smoothed-penalized problem $(\mathcal{P}_{\alpha, \varepsilon})$. Then there exists a globally optimal point $(\bar{y}, \bar{u}) \in V \times L^2(\Omega)$ for the original problem (\mathcal{P}) such that*

$$(y_\alpha, u_\alpha) \rightarrow (\bar{y}, \bar{u}) \text{ in } V \times L^2(\Omega).$$

From an algorithmic point of view, however, finding global solutions of an optimization problem can be a difficult task. It is therefore preferable to use an analysis that relies on stationary points only. In [23] some stationarity concepts resembling those of finite dimensional MPECs (see, e.g., [29, 30, 32]) were introduced for the infinite dimensional problem (1.1).

In this section we derive optimality conditions for the smoothed-penalized problem and show that accumulation points of such stationary points satisfy the conditions of so called \mathcal{E} -almost C-stationarity for the original problem (\mathcal{P}) ; see Definition 3.2, which generalizes the corresponding definitions to accomodate the bilateral control constraints. For the sake of brevity we set $\Omega^+ := \{\mathbf{x} \in \Omega : y(\mathbf{x}) > 0\}$.

Definition 3.2. *The point $(y, u) \in V \times L^2(\Omega)$ is called \mathcal{E} -almost C-stationary for problem (1.1), if there exist $\xi, \phi^a, \phi^b \in L^2(\Omega)$, $p \in V$ and $\lambda \in V^*$ such that the following system is satisfied:*

$$\begin{aligned} (3.2a) \quad & y - \lambda + \mathcal{A}^* p = y_d, \\ (3.2b) \quad & \nu u - p + \phi^b - \phi^a = 0, \\ (3.2c) \quad & \mathcal{A}y - u - \xi = f, \\ (3.2d) \quad & \xi \geq 0 \text{ a.e., } y \geq 0, (y, \xi) = 0, \\ (3.2e) \quad & u - a \geq 0 \text{ a.e., } \phi^a \geq 0 \text{ a.e., } (u - a, \phi^a) = 0, \\ (3.2f) \quad & b - u \geq 0 \text{ a.e., } \phi^b \geq 0 \text{ a.e., } (b - u, \phi^b) = 0, \\ (3.2g) \quad & \langle \lambda, p \rangle \leq 0, \langle \lambda, y \rangle = 0, \\ (3.2h) \quad & p = 0 \text{ a.e. in } \{\xi > 0\}, \end{aligned}$$

and furthermore for every $\tau > 0$ there exists a subset $E_\tau \subset \Omega^+$ with $\text{meas}(\Omega^+ \setminus E_\tau) \leq \tau$ such that

$$(3.3) \quad \langle \lambda, \phi \rangle = 0 \quad \forall \phi \in V, \phi = 0 \text{ a.e. in } \Omega \setminus E_\tau.$$

If $a \equiv -\infty$ and $b \equiv +\infty$ then $\phi^a \equiv \phi^b \equiv 0$. Hence (3.2b) yields $\nu u = p \in V$.

As the penalty approach acts as a relaxation of the feasible domain of the MPEC, standard theory can be applied to derive first order optimality conditions for the smoothed penalized problem $(\mathcal{P}_{\alpha, \varepsilon})$; see, e.g., Zowe and Kurcyusz [33].

Theorem 3.3. *Let $\alpha, \varepsilon > 0$ and $(y, u) \in V \times L^2(\Omega)$ be an optimal solution of (3.1). Then there exists an adjoint state $p \in V$, and multipliers $\phi^a, \phi^b \in L^2(\Omega)$ such that*

$$(3.4a) \quad y + \mathcal{A}^* p + \frac{1}{\alpha} \max'_\varepsilon(0, -y)p = y_d,$$

$$(3.4b) \quad \nu u - p + \phi^b - \phi^a = 0,$$

$$(3.4c) \quad \mathcal{A}y - \frac{1}{\alpha} \max_\varepsilon(0, -y) = u + f,$$

$$(3.4d) \quad u - a \geq 0 \text{ a.e., } \phi^a \geq 0 \text{ a.e., } (u - a, \phi^a) = 0,$$

$$(3.4e) \quad b - u \geq 0 \text{ a.e., } \phi^b \geq 0 \text{ a.e., } (b - u, \phi^b) = 0.$$

The proof of Theorem 3.3 can be found in the Appendix. Setting $\phi := \phi_b - \phi_a$, and introducing $v^+ := \max(0, v)$, $v^- := \max(0, -v)$ for $v \in L^2(\Omega)$ the complementarity system (3.4d)-(3.4e) is equivalent to

$$(3.5) \quad \phi = (\phi + c(u - b))^+ - (\phi + c(u - a))^-,$$

where $c > 0$ is an arbitrary constant.

We now state the main result of this paper describing the convergence properties of stationary points of the smoothed penalized problem with respect to the penalty and smoothing parameters.

Theorem 3.4. *Consider the smooth penalized problem with bounds $a, b \in L^2(\Omega)$ and a C^1 -regularization of the max-operator. Let $\{\alpha\}$ and $\{\varepsilon(\alpha)\}$ satisfy Assumption 2.1. For every $\alpha > 0$ let $(y_\alpha, u_\alpha) \in V \times L^2(\Omega)$ be stationary points of the smooth penalized problem (3.1) with corresponding adjoint state $p_\alpha \in V$ and multipliers $\phi_\alpha^a, \phi_\alpha^b \in L^2(\Omega)$.*

Then there exist $(\tilde{y}, \tilde{u}, \tilde{\xi}, \tilde{p}, \tilde{\phi}^a, \tilde{\phi}^b, \tilde{\lambda}) \in V \times L^2(\Omega) \times L^2(\Omega) \times V \times L^2(\Omega) \times L^2(\Omega) \times V^$ and a subsequence (again denoted by $\{\alpha\}$) such that $y_\alpha \rightarrow \tilde{y}$ in V , $u_\alpha \rightarrow \tilde{u}$ in $L^2(\Omega)$, $\frac{1}{\alpha} \max_{\varepsilon(\alpha)}(0, -y_\alpha) \rightarrow \tilde{\xi}$ in V^* , $p_\alpha \rightarrow \tilde{p}$ in V , $\phi_\alpha^a \rightarrow \tilde{\phi}^a$ in $L^2(\Omega)$, $\phi_\alpha^b \rightarrow \tilde{\phi}^b$ in $L^2(\Omega)$ and $-\frac{1}{\alpha} \max'_{\varepsilon(\alpha)}(0, -y_\alpha)p_\alpha \rightharpoonup \tilde{\lambda}$ in V^* , where (\tilde{y}, \tilde{u}) is \mathcal{E} -almost C -stationary for the MPEC (1.1).*

Proof. For the sake of readability we omit the argument of the smoothing parameter and write ε instead of $\varepsilon(\alpha)$.

From the bilateral constraints (3.4d) and (3.4e) it follows that $\{\|u_\alpha\|_{L^2}\}$ is bounded. Therefore there exists $\tilde{u} \in L^2(\Omega)$ and a subsequence (denoted the same) such that u_α converges to \tilde{u} weakly in $L^2(\Omega)$ and strongly in V^* . The sets $\{v \in L^2(\Omega) : v \geq a \text{ a.e. in } \Omega\}$ and $\{v \in L^2(\Omega) : v \leq b \text{ a.e. in } \Omega\}$ are convex and closed and therefore weakly closed. Hence the limit element satisfies

$$(3.6) \quad a \leq \tilde{u} \leq b \text{ a.e. in } \Omega.$$

Using the convergence of u_α in V^* , Theorem 2.3 yields the existence of $\tilde{y} \in V$ with $y_\alpha \rightarrow \tilde{y}$ in V and (\tilde{y}, \tilde{u}) solving the variational inequality (1.1a). Due to the theory of variational inequalities (see e.g. [24]) the VI can further be reformulated in primal-dual or complementarity form. Introducing a slack variable (Lagrange multiplier) $\tilde{\xi} \in L^2(\Omega)$ the VI can equivalently be written as

$$\mathcal{A}\tilde{y} - \tilde{\xi} = \tilde{u} + f, \quad \tilde{y} \geq 0, \quad \tilde{\xi} \geq 0, \quad (\tilde{y}, \tilde{\xi})_{L^2} = 0.$$

Setting

$$\xi_\alpha := \frac{1}{\alpha} \max_\varepsilon(0, -y_\alpha),$$

we find that

$$\xi_\alpha = \mathcal{A}y_\alpha - u_\alpha - f \rightarrow \mathcal{A}\tilde{y} - \tilde{u} - f = \tilde{\xi} \quad \text{in } V^*.$$

Multiplying the adjoint equation (3.4a) by p_α and using the coercivity of the operator \mathcal{A} and the fact that $\max'_\varepsilon(0, r) \in [0, 1]$ for all $\varepsilon > 0$ and $r \in \mathbb{R}$, we estimate

$$\begin{aligned} C_C \|p_\alpha\|_V^2 &\leq \langle \mathcal{A}^* p_\alpha, p_\alpha \rangle = \langle y_d - y_\alpha, p_\alpha \rangle - \frac{1}{\alpha} \int_\Omega \max'_\varepsilon(0, -y_\alpha) p_\alpha^2 dx \\ &\leq \|y_d - y_\alpha\|_{V^*} \|p_\alpha\|_V. \end{aligned}$$

Therefore $\{p_\alpha\}$ is bounded in V and there exists another subsequence (again denoted the same) and an element $\tilde{p} \in V$ such that $p_\alpha \rightharpoonup \tilde{p}$ in V .

Next we show the strong convergence of u_α and the multipliers ϕ_α^a and ϕ_α^b and establish (3.2e) and (3.2f). Due to the boundedness of u_α and p_α in $L^2(\Omega)$ (3.4b) yields the boundedness of

$$\phi_\alpha := (\phi_\alpha^b - \phi_\alpha^a)$$

in $L^2(\Omega)$. From the complementarity systems (3.4d) and (3.4e) we deduce that the sets $\{\phi_\alpha^a > 0\}$ and $\{\phi_\alpha^b > 0\}$ are disjoint. Therefore

$$\phi_\alpha^a = \max(-\phi_\alpha, 0), \quad \phi_\alpha^b = \max(\phi_\alpha, 0).$$

The Lipschitz continuity of the operator $\max(\cdot, 0) : L^2(\Omega) \rightarrow L^2(\Omega)$ together with the boundedness of $\{\phi_\alpha\}$ then yields the boundedness of $\{\phi_\alpha^a\}$ and $\{\phi_\alpha^b\}$ in $L^2(\Omega)$. Hence there exist $\tilde{\phi}^a, \tilde{\phi}^b \in L^2(\Omega)$ and a subsequence (again denoted the same), such that

$$\phi_\alpha^a \rightharpoonup \tilde{\phi}^a, \quad \phi_\alpha^b \rightharpoonup \tilde{\phi}^b$$

in $L^2(\Omega)$. Using (3.4b) again, we conclude that

$$(3.7) \quad \nu \tilde{u} - \tilde{p} + \tilde{\phi}^b - \tilde{\phi}^a = 0.$$

As before we argue that the set $\{v \in L^2(\Omega) : v \geq 0 \text{ a.e. in } \Omega\}$ is weakly closed, hence

$$(3.8) \quad \tilde{\phi}^a \geq 0, \quad \tilde{\phi}^b \geq 0 \quad \text{a.e. in } \Omega.$$

Multiplying (3.7) by \tilde{u} yields

$$(3.9) \quad \nu \|\tilde{u}\|^2 - (\tilde{p}, \tilde{u}) + (\tilde{\phi}^b, b) - (\tilde{\phi}^a, a) = (\tilde{\phi}^b, b - \tilde{u}) + (\tilde{\phi}^a, \tilde{u} - a).$$

On the other hand multiplying (3.4b) by u_α and considering the complementarity conditions (3.4d) and (3.4e), we find

$$(3.10) \quad \nu \|u_\alpha\|^2 - (p_\alpha, u_\alpha) + (\phi_\alpha^b, b) - (\phi_\alpha^a, a) = (\phi_\alpha^b, b - u_\alpha) + (\phi_\alpha^a, u_\alpha - a) = 0.$$

Passing to the limit $\alpha \rightarrow 0$ yields

$$(3.11) \quad \nu \|\tilde{u}\|^2 \leq \nu \liminf \|u_\alpha\|^2 = (\tilde{p}, \tilde{u}) - (\tilde{\phi}^b, b) + (\tilde{\phi}^a, a).$$

Comparing (3.11) to (3.9), we see that

$$(\tilde{\phi}^b, b - \tilde{u}) + (\tilde{\phi}^a, \tilde{u} - a) \leq 0.$$

Using (3.6) and (3.8) we find that

$$(\tilde{\phi}^b, b - \tilde{u}) = (\tilde{\phi}^a, \tilde{u} - a) = 0.$$

Equations (3.9) and (3.10) then yield

$$\|\tilde{u}\|^2 = \lim \|u_\alpha\|^2.$$

This together with weak the convergence of u_α yields strong convergence in $L^2(\Omega)$. Consequently $\phi_\alpha = \phi_\alpha^b - \phi_\alpha^a$ converges strongly in $L^2(\Omega)$ and due to the Lipschitz continuity of $\max(\cdot, 0)$ the multipliers ϕ_α^a and ϕ_α^b individually converge strongly in $L^2(\Omega)$.

We now direct our attention to the multiplier $\tilde{\lambda}$. Setting

$$\lambda_\alpha := -\frac{1}{\alpha} \max'_\varepsilon(0, -y_\alpha)p_\alpha,$$

and considering the adjoint equations (3.4a) and (3.2a), we find that $\lambda_\alpha \rightarrow \tilde{\lambda}$ in V^* . Next we show that $\langle \tilde{\lambda}, \tilde{y} \rangle = 0$.

For \max_ε^g we find that $(\max_\varepsilon^g)'(0, r) = 0$ for all $r \leq 0$. Hence

$$\langle \lambda_\alpha, y_\alpha^+ \rangle = \langle -\frac{1}{\alpha} (\max_\varepsilon^g)'(0, -y_\alpha)p_\alpha, y_\alpha^+ \rangle = 0 \quad \forall \alpha > 0,$$

where $y_\alpha^+ := \max(0, y_\alpha)$. As $y_\alpha \rightarrow \tilde{y}$ in V , also $y_\alpha^+ \rightarrow \tilde{y}^+ = \tilde{y}$ in V (see Lemma A.1 in the Appendix). Hence

$$\langle \tilde{\lambda}, \tilde{y} \rangle = \lim_{\alpha \rightarrow 0} \langle \lambda_\alpha, y_\alpha^+ \rangle = \lim_{\alpha \rightarrow 0} 0 = 0.$$

For \max_ε^l it is easy to see that $(\max_\varepsilon^l)'(0, r) \in [0, \frac{1}{2}]$ for all $r \leq 0$. Exploiting the fact that $\varepsilon/\alpha \rightarrow 0$ we find that

$$|\langle \lambda_\alpha, y_\alpha^+ \rangle| \leq \frac{1}{\alpha} \int_{\{0 \leq y_\alpha \leq \varepsilon\}} |(\max_\varepsilon^l)'(0, -y_\alpha)p_\alpha y_\alpha| dx \leq \frac{\varepsilon}{2\alpha} \int_{\{0 \leq y_\alpha \leq \varepsilon\}} |p_\alpha| dx \rightarrow 0,$$

as p_α is bounded in $L^1(\Omega)$. Hence also in this case $\langle \tilde{\lambda}, \tilde{y} \rangle = 0$.

We now show that $\langle \tilde{\lambda}, \tilde{p} \rangle \leq 0$. Multiplying the adjoint equation (3.4a) by p_α yields

$$\langle \mathcal{A}^* p_\alpha, p_\alpha \rangle + \langle y_\alpha - y_d, p_\alpha \rangle = -\frac{1}{\alpha} \langle \max'_\varepsilon(0, -y_\alpha)p_\alpha, p_\alpha \rangle \leq 0 \quad \forall \alpha > 0.$$

Due to boundedness and coercivity of \mathcal{A}^* , we find that

$$\langle \mathcal{A}^* \tilde{p}, \tilde{p} \rangle + \langle \tilde{y} - y_d, \tilde{p} \rangle \leq \liminf_{\alpha \rightarrow 0} (\langle \mathcal{A}^* p_\alpha, p_\alpha \rangle + \langle y_\alpha - y_d, p_\alpha \rangle) \leq 0.$$

Using (3.2a), we see that this is equivalent to

$$\langle \tilde{\lambda}, \tilde{p} \rangle \leq 0.$$

We next show the condition for $\tilde{\lambda}$ in $\{\tilde{y} > 0\}$. Note that $y_\alpha \rightarrow \tilde{y}$ in V and hence also in $L^2(\Omega)$. Therefore there exists a subsequence (denoted the same) such that $y_\alpha \rightarrow \tilde{y}$ point-wise a.e. in Ω . Now let $\mathbf{x} \in \{\tilde{y} > 0\}$. Then there exists $\alpha_1 > 0$ such that

$$y_\alpha(\mathbf{x}) > \frac{\tilde{y}(\mathbf{x})}{2} > 0$$

for all $\alpha < \alpha_1$. If we use regularization \max_ε^g , we immediately see that for all $\alpha < \alpha_1$ this yields that $(\max_\varepsilon^g)'(0, -y_\alpha(\mathbf{x})) = 0$ and hence $\lambda_\alpha(\mathbf{x}) = 0$. If regularization

\max_{ε}^l is used, we furthermore know that $\varepsilon(\alpha) \rightarrow 0$. Hence there exists $\alpha_2 > 0$ such that

$$\varepsilon(\alpha) < \frac{\tilde{y}(\mathbf{x})}{2}$$

for all $\alpha < \alpha_2$. We therefore find that

$$-y_\alpha(\mathbf{x}) < -\varepsilon(\alpha)$$

for all $\alpha < \min(\alpha_1, \alpha_2)$, and hence $\lambda_\alpha(\mathbf{x}) = 0$ for all $\alpha < \min(\alpha_1, \alpha_2)$. We therefore find that in both cases

$$\lambda_\alpha \rightarrow 0 \quad \text{p.w. a.e. in } \{\tilde{y} > 0\}.$$

Using Egorov's Theorem this yields the condition for $\tilde{\lambda}$ required for \mathcal{E} -almost C-stationarity.

What remains to show is that $\tilde{p} = 0$ a.e. in $\{\tilde{\xi} > 0\}$. First we take a look at the global regularization \max_{ε}^g . For the sake of brevity we define the sets

$$M_1 = M_1(\alpha) := \{0 < -y_\alpha < \varepsilon\}, \quad M_2 = M_2(\alpha) := \{-y_\alpha \geq \varepsilon\}.$$

Due to the convergence of $(\xi_\alpha, y_\alpha) \rightarrow 0$ we find that

$$(3.12) \quad (\xi_\alpha, y_\alpha) = \frac{1}{\alpha} \int_{M_1} \frac{1}{2\varepsilon} y_\alpha^3 + \frac{1}{\alpha} \int_{M_2} (-y_\alpha - \frac{\varepsilon}{2}) y_\alpha \rightarrow 0.$$

As both terms of the sum are non-positive we see that they both individually tend to zero. For the first term on the right hand side of (3.12) this yields

$$(3.13) \quad \left\| \frac{1}{\sqrt{\alpha\varepsilon}} \chi_{M_1} |y_\alpha|^{3/2} \right\|_{L^2} \rightarrow 0.$$

Further note that due to the definition of M_2 we have the estimate

$$|y_\alpha(\mathbf{x}) + \frac{\varepsilon}{2}| = -y_\alpha(\mathbf{x}) - \frac{\varepsilon}{2} \leq -y_\alpha(\mathbf{x}) = |y_\alpha(\mathbf{x})|$$

for almost every $\mathbf{x} \in M_2$. This estimate together with the second term of the sum on the right hand side of (3.12) then yields

$$(3.14) \quad \left\| \frac{1}{\sqrt{\alpha}} \chi_{M_2} (y_\alpha + \frac{\varepsilon}{2}) \right\|_{L^2} \rightarrow 0.$$

Next recall that $\{\lambda_\alpha\}$ and $\{p_\alpha\}$ are bounded in V^* and V , respectively. Therefore $|\langle \lambda_\alpha, p_\alpha \rangle| \leq C$ for some constant $C > 0$ independent of α . The definition of λ_α then yields

$$(3.15) \quad \begin{aligned} |\langle \lambda_\alpha, p_\alpha \rangle| &= \left| -\frac{1}{\alpha} \int_{M_1} \frac{1}{\varepsilon} (-y_\alpha) p_\alpha^2 - \frac{1}{\alpha} \int_{M_2} p_\alpha^2 \right| \\ &= \frac{1}{\alpha} \int_{M_1} \frac{1}{\varepsilon} (-y_\alpha) p_\alpha^2 + \frac{1}{\alpha} \int_{M_2} p_\alpha^2 \leq C. \end{aligned}$$

As again both terms of the sum have the same sign, we find that they are both individually bounded by C , i.e.,

$$(3.16) \quad \left\| \frac{1}{\sqrt{\alpha\varepsilon}} \chi_{M_1} |y_\alpha|^{1/2} p_\alpha \right\|_{L^2}^2 \leq C \quad \wedge \quad \left\| \frac{1}{\sqrt{\alpha}} \chi_{M_2} p_\alpha \right\|_{L^2}^2 \leq C.$$

Furthermore as both integrands are non-negative we furthermore find that they remain bounded if we only integrate over a subset. Hence

$$(3.17) \quad \left\| \frac{1}{\sqrt{\alpha\varepsilon}} \chi_{M_1} |y_\alpha|^{1/2} p_\alpha^+ \right\|_{L^2}^2 \leq C \quad \wedge \quad \left\| \frac{1}{\sqrt{\alpha}} \chi_{M_2} p_\alpha^+ \right\|_{L^2}^2 \leq C.$$

Combining (3.13), (3.14) and (3.16), we find that

$$(3.18) \quad (\xi_\alpha, p_\alpha) = \frac{1}{2} \left(\frac{1}{\sqrt{\alpha\varepsilon}} \chi_{M_1} y_\alpha^{3/2}, \frac{1}{\sqrt{\alpha\varepsilon}} \chi_{M_1} y_\alpha^{1/2} p_\alpha \right) - \left(\frac{1}{\sqrt{\alpha}} \chi_{M_2} (y_\alpha + \frac{\varepsilon}{2}), \frac{1}{\sqrt{\alpha}} \chi_{M_2} p_\alpha \right) \rightarrow 0.$$

Therefore

$$(3.19) \quad (\tilde{\xi}, \tilde{p}) = 0.$$

Note that due to (3.17) the computations in (3.18) also apply if p_α is replaced by p_α^+ . Therefore using the weak convergence of p_α^+ to \tilde{p}^+ in V (see Lemma A.1) we find that also $(\tilde{\xi}, \tilde{p}^+) = 0$. The non-negativity of $\tilde{\xi}$ then ensures that $\tilde{p} = 0$ a.e. in $\{\tilde{\xi} > 0\}$.

Finally we show that $\tilde{p} = 0$ a.e. in $\{\tilde{\xi} > 0\}$ if regularization \max_ε^l is used. The proof is along the same lines as for the global regularization but is somewhat simplified by the fact that we can use the property $\varepsilon/\alpha \rightarrow 0$. We find that the part of ξ_α defined on $\{|y_\alpha| < \varepsilon\}$ can be neglected. In fact

$$\|\xi_\alpha\|_{L^2(\{|y_\alpha| < \varepsilon\})}^2 = \frac{1}{\alpha^2} \int_{\{|y_\alpha| < \varepsilon\}} \left(\frac{1}{4\varepsilon} y_\alpha^2 - \frac{1}{2} y_\alpha + \frac{\varepsilon}{4} \right)^2 \leq \left(\frac{\varepsilon}{\alpha} \right)^2 \int_{\{|y_\alpha| < \varepsilon\}} \left(\frac{1}{4} + \frac{1}{2} + \frac{1}{4} \right) \rightarrow 0.$$

Hence we find that

$$(3.20) \quad \hat{\xi}_\alpha := -\frac{1}{\alpha} \chi_{M_2} y_\alpha \rightarrow \tilde{\xi} \quad \text{in } V^*.$$

Using the boundedness of $\langle \lambda_\alpha, p_\alpha \rangle$ it can be shown that both $\|\frac{1}{\sqrt{\alpha}} \chi_{M_2} p_\alpha\|_{L^2}$ and $\|\frac{1}{\sqrt{\alpha}} \chi_{M_2} p_\alpha^+\|_{L^2}$ are bounded. Furthermore it follows from the fact that $(\hat{\xi}_\alpha, y_\alpha) \rightarrow 0$ that $\|\frac{1}{\sqrt{\alpha}} \chi_{M_2} y_\alpha\|_{L^2} \rightarrow 0$. Then

$$(\hat{\xi}_\alpha, p_\alpha) = -\left(\frac{1}{\sqrt{\alpha}} \chi_{M_2} y_\alpha, \frac{1}{\sqrt{\alpha}} \chi_{M_2} p_\alpha \right) \rightarrow 0.$$

This yields $(\tilde{\xi}, \tilde{p}) = 0$ and similarly $(\tilde{\xi}, \tilde{p}^+) = 0$ and thus the desired property for \tilde{p} . \square

Remark 3.5. (i) The results of Theorem 3.4 remain true if \max_ε^g is replaced by \max_ε^G . In the proof the specific definition of the operator is only used to show that $\tilde{p} = 0$ a.e. on $\{\tilde{\xi} > 0\}$. For the operator \max_ε^G the same proof technique can be employed as for \max_ε^g , if the inequality

$$0 \leq \frac{y_\alpha^2}{\varepsilon^2} + \frac{y_\alpha^3}{2\varepsilon^3} \leq \frac{1}{2} \left(\frac{3y_\alpha^2}{\varepsilon^2} + \frac{2y_\alpha^3}{\varepsilon^3} \right) \text{ a.e. in } M_1$$

is used in step (3.18).

(ii) If $a \equiv -\infty$ or $b \equiv \infty$ is chosen, the results of Theorem 3.4 hold true if additionally the boundedness of $\{u_\alpha\}$ in $L^2(\Omega)$ is assumed. In the control-unconstrained case, i.e., $a \equiv -\infty$, $b \equiv \infty$, the optimality condition (3.4b) is simplified to $u_\alpha = \frac{1}{\nu} p_\alpha$. Therefore u_α adopts the regularity of p_α and we find that $\tilde{u} \in V$ and $u_\alpha \rightharpoonup \tilde{u}$ in V .

4. THE ALGORITHM

The constructive nature of Theorem 3.4 implies an infinite dimensional solution algorithm for the MPEC problem (\mathcal{P}) , where the solution is approximated by the solution of the smoothed penalized problems $(\mathcal{P}_{\alpha,\varepsilon})$ along a sequence $\{(\alpha, \varepsilon(\alpha))\}$. This outer algorithm is described in Algorithm 1. Theorem 3.4 then yields the

Algorithm 1 (Outer Algorithm)

Data: $y_d, f, \alpha_0, \varepsilon_0$.

- 1: Choose (y^0, u^0, p^0) and set $k := 0$.
 - 2: **repeat**
 - 3: Solve the first order system (3.4) with $(\alpha, \varepsilon) = (\alpha_k, \varepsilon_k)$, to obtain $(y^{k+1}, u^{k+1}, p^{k+1})$ using initial values (y^k, u^k, p^k) for solution algorithm.
 - 4: Choose $\alpha_{k+1} < \alpha_k$ and ε_{k+1} .
 - 5: Set $k := k + 1$.
 - 6: **until** some stopping rule is satisfied.
-

convergence of the iterates to a point that is \mathcal{E} -almost C-stationary for the MPEC problem. The state variable y_α and the adjoint p_α converge in V strongly and weakly, respectively. In the control unconstrained case the control u_α also converges weakly in V . Whereas if point-wise bilateral constraints are imposed on the control, then u_α only converges (strongly) in $L^2(\Omega)$. Numerical results illustrating the approximation error of the state y_α with respect to the penalty parameter are given in Section 5.3.

4.1. Solving the subproblem. For the numerical realization of Algorithm 1 the subproblems are discretized using a uniform grid with mesh size h . The resulting large nonlinear systems are solved by employing two different multigrid techniques. The first approach uses the Full Approximation Scheme (FAS) due to Brandt [10], to solve the optimality system for the state y and the adjoint state p (see also [8, 9, 7]). In the second approach the optimality conditions are reduced to a fixed-point equation in the control u and solved using a nonlinear multigrid method of second kind (see Hackbusch, [15, 16, 17, 18, 19]).

4.1.1. FAS multigrid. In the optimality system (3.4) the choice of $c = \nu$ in (3.5) enables us to eliminate the control u , using (3.4b). The resulting reduced nonlinear system reads

$$(4.1) \quad \begin{aligned} y + \mathcal{A}^* p + \frac{1}{\alpha} \max'_\varepsilon(0, -y)p &= y_d, \\ \mathcal{A}y - \frac{1}{\alpha} \max_\varepsilon(0, -y) - \frac{1}{\nu}p + \max(0, \frac{1}{\nu}p - b) - \max(0, -\frac{1}{\nu}p + a) &= f. \end{aligned}$$

This system is subsequently solved using a FAS method [10], which is a natural choice when solving nonlinear PDE-based problems. We briefly outline the method and propose a smoothing technique which is tailored to the specific problem under consideration.

For a given sequence of grids let h denote the size of the current grid and $H > h$ denote the mesh size of the next coarser grid. Furthermore let U_h and U_H denote the finite dimensional subspaces of $L^2(\Omega)$ corresponding to the mesh sizes h and H . Let $I_h^H : U_h \rightarrow U_H$ and $\hat{I}_h^H : U_h \rightarrow U_H$ denote the restriction operators using full weighting and straight injection, respectively, and let $I_H^h : U_H \rightarrow U_h$ denote the

interpolation operator using linear interpolation (see, e.g., [19] for the definition of the operators). Let y_d^h, f^h denote the discretized data and let $h_{max} > 0$ denote the grid size of the coarsest mesh, i.e., the mesh on which the system is solved exactly. Then the FAS-algorithm for solving the discrete optimality conditions is given by Algorithm 2 (see, e.g., [8, 12]). Note that in step 9 the algorithm is

Algorithm 2 (FAS-algorithm)

Data: (y_d^h, f^h) , initial values (y^h, p^h) .

- 1: **if** $h = h_{max}$ **then**
 - 2: solve (4.1) exactly.
 - 3: **else**
 - 4: Do ν_{pre} pre-smoothing steps.
 - 5: Compute residuals $r_a^h = y_d^h - y^h - (\mathcal{A}^h)^* p^h - \frac{1}{\alpha} \max'_\varepsilon(0, -y^h) p^h$ and $r_s^h = f^h - \mathcal{A}^h y^h + \frac{1}{\alpha} \max_\varepsilon(0, -y^h) - \frac{1}{\nu} p^h$.
 - 6: Restrict residuals to coarser grid using **full weighting** $r_a^H = I_h^H r_a^h$, $r_s^H = I_h^H r_s^h$.
 - 7: Restrict (y^h, p^h) to coarser grid using **straight injection** $y^H = \hat{I}_h^H y^h$, $p^H = \hat{I}_h^H p^h$.
 - 8: Compute right hand sides for coarse problem $y_d^H = r_a^H + y^H + (\mathcal{A}^H)^* p^H + \frac{1}{\alpha} \max'_\varepsilon(0, -y^H) p^H$, $f^H = r_s^H + \mathcal{A}^H y^H - \frac{1}{\alpha} \max_\varepsilon(0, -y^H) - \frac{1}{\nu} p^H$.
 - 9: Apply γ -times the FAS-algorithm to coarse grid problem with $h = H$, right hand side (y_d^H, f^H) and initial values (y^H, p^H) to compute new approximation $(\tilde{y}^H, \tilde{p}^H)$.
 - 10: Coarse grid correction: $y^h = y^H + I_H^h(\tilde{y}^H - y^H)$, $p^h = p^H + I_H^h(\tilde{p}^H - p^H)$, where I_H^h denotes the interpolation operator using **linear interpolation**.
 - 11: Do ν_{post} post-smoothing steps.
 - 12: **end if**
-

recursively applied γ -times. Here $\gamma \in \mathbb{N}$ is called the cycle index. For $\gamma = 1$ the algorithm defines a V-cycle and for $\gamma = 2$ a W-cycle. On the coarsest mesh the system is solved exactly. This exact solve is realized using an iterative solver, e.g., a semismooth-Newton method, with a small stopping tolerance (e.g., $\sqrt{\epsilon_m}$, where ϵ_m is the machine precision), [22]. The integers ν_{pre} and ν_{post} denote the number of smoothing steps that are applied to the approximations of the solution. These numbers are crucial for the convergence of the algorithm. For well conditioned problems $\nu_{pre} = \nu_{post} = 2$ is usually sufficient but as the conditioning becomes worse (e.g., the cost of the control ν becomes small) the number of necessary smoothing steps may increase.

As a smoothing technique we apply a collective nonlinear Gauss-Seidel scheme where the nonlinear scalar equations are solved analytically. For a standard five-point finite difference stencil, the discretized version of system (4.1) is:

$$(4.2) \quad \begin{aligned} y_{ij} + \frac{4}{h^2} p_{ij} + \frac{1}{\alpha} \max'_\varepsilon(0, -y_{ij}) p_{ij} &= B_{ij}, \\ \frac{4}{h^2} y_{ij} - \frac{1}{\alpha} \max_\varepsilon(0, -y_{ij}) - \frac{1}{\nu} p_{ij} + \max(0, \frac{1}{\nu} p_{ij} - b_{ij}) + \max(0, -\frac{1}{\nu} p_{ij} + a_{ij}) &= A_{ij} \end{aligned}$$

with

$$\begin{aligned} B_{ij} &= (y_d)_{ij} + \frac{1}{h^2}(p_{i+1,j} + p_{i-1,j} + p_{i,j+1} + p_{i,j-1}), \\ A_{ij} &= f_{ij} + \frac{1}{h^2}(y_{i+1,j} + y_{i-1,j} + y_{i,j+1} + y_{i,j-1}) \end{aligned}$$

for all inner grid points (i, j) . For given vectors $y^{(k-1)}$ and $p^{(k-1)}$ the smoothed approximations $y^{(k)}$ and $p^{(k)}$ are obtained by solving (4.2) with right hand sides

$$\begin{aligned} B_{ij}^{(k)} &= (y_d)_{ij} + \frac{1}{h^2}(p_{i+1,j}^{(k-1)} + p_{i-1,j}^{(k)} + p_{i,j+1}^{(k-1)} + p_{i,j-1}^{(k)}), \\ A_{ij}^{(k)} &= f_{ij} + \frac{1}{h^2}(y_{i+1,j}^{(k-1)} + y_{i-1,j}^{(k)} + y_{i,j+1}^{(k-1)} + y_{i,j-1}^{(k)}) \end{aligned}$$

for each grid point, looping over the columns and rows. Depending on the realization of \max_ε , the Gauss-Seidel system (4.2) can be reduced to a cubic equation if a C^1 -regularization is used and to an equation of fifth order if the C^2 -regularization is used. As the system has to be solved for every grid point in every smoothing iteration the use of a cost efficient, yet still accurate solution method is of importance. In the C^1 -case the cubic equation is solved analytically using Cardano's method. The solution of a polynomial of order five, however, is more intricate and in general finding an analytical solution is a difficult task. In view of the computational cost the use of the C^1 -regularization therefore seems favorable.

For the overall algorithm the FAS-method is incorporated into a nested iteration technique, utilizing a grid hierarchy for the outer loop as well, where the penalty parameter α is coupled with the mesh size h and an inexact solution technique is used. In each outer iteration the subproblem is solved on a fixed grid for fixed parameters (α, ε) using the FAS-method of Algorithm 2 with a stopping tolerance depending on the current mesh size. After each outer iteration α is decreased. If the penalty parameter goes below a threshold depending on the mesh size, e.g.,

$$(4.3) \quad \alpha \leq Ch^{2/s}$$

where $C > 0$ is a suitably chosen constant (e.g., 0.5), and $s \in (0.5, 1)$, then the mesh is refined. This condition will be motivated in more detail in Section 5.3. The outer algorithm terminates when α_k satisfies (4.3) for the finest mesh.

The results of our numerical tests runs are given in Section 5.5. Although the performance of the method is good, the convergence of the algorithm is still an issue which cannot be guaranteed at this point. We therefore present an alternative multigrid method together with a convergence analysis.

4.1.2. Multigrid method of the second kind. An alternative to the FAS-method is the so called "multigrid iteration of the second kind", a scheme designed to solve fixed-point equations. It uses the multigrid framework, employing Picard's iteration as smoothing step. The convergence of the Picard iteration (contraction of the operator), however, is not necessary for the convergence of the overall algorithm.

In order to apply the multigrid method of second kind we reformulate the optimality conditions of $(\mathcal{P}_{\alpha, \varepsilon})$ as a fixed point problem. We introduce the control-to-state mapping $\Lambda_S : L^2(\Omega) \rightarrow Y$ with $Y := V \cap C(\bar{\Omega})$, i.e., for a given control $v \in L^2(\Omega)$ we define $\Lambda_S(v) = y_\alpha(v)$ as the solution of the state equation

$$\mathcal{A}y_\alpha(v) - \frac{1}{\alpha} \max_{\varepsilon(\alpha)}(0, -y_\alpha(v)) = f + v.$$

We further define the state-to-adjoint mapping $\Lambda_A : Y \rightarrow V$ in a similar way. For given state y the corresponding adjoint state $\Lambda_A(y) = p_\alpha(y)$ is defined as the solution of the adjoint equation

$$(4.4) \quad \mathcal{A}^* p_\alpha(y) + \frac{1}{\alpha} \max'_{\varepsilon(\alpha)}(0, -y)p_\alpha(y) = y_d - y.$$

Again setting $c = \nu$ in (3.5), equation (3.4b) can be formulated as

$$u = \frac{1}{\nu}p - \max(0, \frac{1}{\nu}p - b) + \max(0, -\frac{1}{\nu}p + a),$$

which is equivalent to the projection onto the feasible interval, i.e.,

$$u = P_{[a,b]}(\frac{1}{\nu}p) := \begin{cases} a & \text{where } \frac{1}{\nu}p < a, \\ \frac{1}{\nu}p & \text{where } a \leq \frac{1}{\nu}p \leq b, \\ b & \text{where } \frac{1}{\nu}p > b. \end{cases}$$

The optimality conditions for $(\mathcal{P}_{\alpha,\varepsilon})$ are then equivalent to the fixed-point problem

$$(4.5) \quad u = F(u),$$

with the nonlinear operator $F : L^2(\Omega) \rightarrow L^2(\Omega)$ given by $F(v) = P_{[a,b]}(K(v))$ for every $v \in L^2(\Omega)$ and $K = \frac{1}{\nu}\Lambda_A \circ \Lambda_S$. Note that the evaluation of the operator K requires the solution of one semilinear and one linear elliptic equation.

For the multigrid framework we denote the discrete problems, obtained by discretizing the differential operators and the data by

$$(4.6) \quad u^h = F^h(u^h).$$

Furthermore we consider perturbed problems of the form

$$u^h = F^h(u^h) + d^h,$$

with sufficiently small perturbations d^h . The recursive multigrid method is described in Algorithm 3.

Algorithm 3 (MG2: Recursive multigrid algorithm of second kind)

Data: perturbation d^h , initial value u^h .

- 1: **if** $h = h_{max}$ **then**
 - 2: solve (4.6) exactly.
 - 3: **else**
 - 4: $u^h \leftarrow F^h(u^h) + d^h$ (smoothing).
 - 5: $d^H := I_h^H(u^h - F^h(u^h) - d^h)$.
 - 6: Apply MG2(d^H, \tilde{u}^H) on the next coarser mesh twice to obtain u^H . Here \tilde{u}^H is the solution of (4.6) on the next coarser mesh
 - 7: $u^h := u^h - I_H^h(u^H - \tilde{u}^H)$ (coarse grid correction).
 - 8: **end if**
-

Note that in step 5 already the newly assigned u^h of step 4 is used. Further note that for the application of Algorithm 3 to (4.6) on a given mesh the exact solution of the problem is required on every coarser mesh (\tilde{u}^H is required in step 7). These values are obtained by using a coarse-to-fine method in an outer loop (see the "for-loop" in Algorithm 4): The optimality system (4.6) is solved on the coarsest given mesh of mesh size h_{max} using a non-smooth solver, e.g., a semismooth Newton method, [22]. Using this information, the problem is then solved on the next finer grid using the multigrid method. The exact solutions on the respective next

coarser meshes are hence obtained utilizing a nested iteration initialization technique, similar to the full multigrid idea [19]. Solving problem (4.6) on the finest mesh of mesh size h_{min} therefore requires several applications of Algorithm 3 on the various meshes, resulting in a relatively large computational cost.

For fixed (α, ε) only the non-smooth solver on the coarsest mesh requires a good initialization, as the multigrid algorithms on the various meshes are always initialized by \tilde{u}^H on the respective next coarser meshes. The continuation method via the penalty and the smoothing parameter (Algorithm 1) described in the previous section is therefore only necessary for the non-smooth solver on the coarsest grid of mesh size $h_{max} = h_0$ (see the "while-loop" in Algorithm 4). The complete method is given in Algorithm 4.

Algorithm 4 (Outer loop for a multigrid Algorithm of second kind)

Data: $(\alpha_1, \varepsilon_1, \alpha_{min}) > 0$, initial guess u^0 on mesh h_0 , sequence of grids $\{h_j\}_{j=0}^M$.
Set $k = 1$.

- 1: **while** $\alpha_k > \alpha_{min}$ **do**
- 2: Compute solution u^k of (4.6) with $\alpha = \alpha_k$, $\varepsilon = \varepsilon_k$ and initial guess u^{k-1} on grid h_0 using semismooth Newton.
- 3: Choose α_{k+1} , ε_{k+1} and set $k := k + 1$.
- 4: **end while**
- 5: Set $h := h_0$, $\tilde{u}^h := u^{k-1}$, $\alpha := \alpha_{k-1}$, $\varepsilon := \varepsilon_{k-1}$.
- 6: **for** $j = 1$ to M **do**
- 7: Set $H := h$, $h := h_j$.
- 8: Compute \tilde{u}^h , the result of $\text{MG2}(0, I_H^h \tilde{u}^H)$.
- 9: **end for**

In [17] Hackbusch gives conditions for the convergence of the nonlinear multigrid-method of second kind. For suitable choices of the restriction and the prolongation operators it is sufficient to show that F (and the discrete operators F^h) satisfies a Lipschitz condition of the form

$$(4.7) \quad F(v) - F(w) = L(v, w)(v - w), \quad \forall v, w \in L^2(\Omega),$$

where L is a bounded linear operator

$$(4.8) \quad \|L(v, w)\|_{L^2, L^2} \leq C, \quad \forall v, w \in L^2(\Omega).$$

Furthermore we have to show that $L(\cdot, \cdot)$ is continuous at the solution u^* of (4.5), i.e.,

$$(4.9) \quad \|L(v, w) - L(u^*, w)\|_{L^2, L^2} \rightarrow 0, \quad \text{if } v, w \rightarrow u^*.$$

If these conditions hold, the algorithm converges for sufficiently large values of h_{max} . We observe that such a property of $L(\cdot, \cdot)$ can only hold true in non-degenerate situations, i.e., when the set where F is not differentiable has measure zero.

Motivated by [16] we construct the operator L using a mean-value representation for which we require the differentiability of the control-to-adjoint mapping K . The operator Λ_S , mapping the control to the state variable, is Fréchet differentiable from $L^2(\Omega)$ to Y , see, e.g., [31]. The adjoint equation, however, contains the term $\max'_\varepsilon(0, -y)$. Hence Λ_A need not be differentiable if the regularization \max_ε is only C^1 . We will therefore restrict ourselves to the C^2 -regularization for this multigrid

method and show that in this case the state-to-adjoint mapping is differentiable from Y to V .

Lemma 4.1. *Let $\Lambda_A : Y \rightarrow V$ denote the state-to-adjoint operator defined by (4.4) with $\max_\varepsilon = \max_\varepsilon^G$. Then Λ_A is Fréchet differentiable for every $y \in Y$.*

Proof. Due to the monotonicity of the \max_ε^G -operator, the linear operator

$$\mathcal{A}^* + \frac{1}{\alpha}(\max_\varepsilon^G)'(0, -y) : V \rightarrow V^*$$

is bounded and coercive with constants independent of y . Then from the Lax-Milgram Theorem it follows that the operator is invertible and the norm of the inverse is bounded independently of y . Hence, the operator Λ_A is well defined. The Lipschitz continuity of $(\max_\varepsilon^G)'(0, \cdot) : Y \rightarrow L^\infty(\Omega)$ furthermore yields the local Lipschitz continuity of Λ_A .

Note that the Nemyzki operator $y \mapsto \phi(y) := (\max_\varepsilon^G)'(0, -y)$ is Fréchet differentiable from Y to $L^\infty(\Omega)$. Now let $y, \delta y \in Y$ be given and set $p_1 = \Lambda_A(y + \delta y)$, $p_2 = \Lambda_A(y)$. Subtraction of the corresponding adjoint equations (4.4) then yields

$$\begin{aligned} 0 &= \mathcal{A}^*(p_1 - p_2) + \phi(y + \delta y)p_1 - \phi(y)p_2 + \delta y \\ (4.10) \quad &= (\mathcal{A}^* + \phi(y))(p_1 - p_2) + (\phi(y + \delta y) - \phi(y))p_1 + \delta y \\ &= (\mathcal{A}^* + \phi(y))(p_1 - p_2) + (\phi'(y)\delta y + r_y(y, \delta y))p_1 + \delta y, \end{aligned}$$

where $\|r_y(y, \delta y)\|_{L^\infty} = \mathcal{O}(\|\delta y\|_Y)$. Setting

$$\begin{aligned} D\Lambda_A(y) &= -(\mathcal{A}^* + \phi(y))^{-1}(\phi'(y)p_2 + I), \\ r_\Lambda(y, \delta y) &= -(\mathcal{A}^* + \phi(y))^{-1}(\phi'(y)\delta y(p_1 - p_2) + r_y(y, \delta y)p_1), \end{aligned}$$

equation (4.10) can be reformulated as

$$\Lambda_A(y + \delta y) - \Lambda_A(y) = D\Lambda_A(y)\delta y + r_\Lambda(y, \delta y).$$

Due to the boundedness of $(\mathcal{A}^* + \phi(y))^{-1}$ in $\mathcal{L}(V^*, V)$ and the boundedness of ϕ' in $L^\infty(\Omega)$ we find that $D\Lambda_A(y)$ is linear and bounded. The Lipschitz continuity of Λ_A furthermore yields that $\|r_\Lambda(y, \delta y)\|_V = \mathcal{O}(\|\delta y\|_Y)$, hence Λ_A is Fréchet differentiable. \square

Using the chain rule we therefore find that the composite mapping $K = \frac{1}{\nu}\Lambda_A \circ \Lambda_S$ is Fréchet differentiable from $L^2(\Omega)$ to V . Setting $B(v, w) = \int_0^1 K'(w + t(v - w))dt$ for every $v, w \in L^2(\Omega)$, Taylor's theorem yields

$$(4.11) \quad K(v) - K(w) = B(v, w)(v - w).$$

We can now define the Lipschitz operator $L : L^2(\Omega) \times L^2(\Omega) \rightarrow \mathcal{L}(L^2(\Omega), L^2(\Omega))$ by setting $L(v, w) := \theta(v, w)B(v, w)$ with $\theta : L^2(\Omega) \times L^2(\Omega) \rightarrow L^\infty(\Omega)$ defined by

$$(4.12) \quad \theta(v, w) := \begin{cases} 0 & \text{if } K(v) < a, K(w) < a, \\ 1 & \text{if } K(v) \in [a, b], K(w) \in [a, b], \\ 0 & \text{if } K(v) > b, K(w) > b, \\ (K(v) - a)/(B(v, w)(v - w)) & \text{if } K(v) \in [a, b], K(w) < a, \\ (a - K(w))/(B(v, w)(v - w)) & \text{if } K(v) < a, K(w) \in [a, b], \\ (K(v) - b)/(B(v, w)(v - w)) & \text{if } K(v) \in [a, b], K(w) > b, \\ (b - K(w))/(B(v, w)(v - w)) & \text{if } K(v) > b, K(w) \in [a, b], \\ (b - a)/(B(v, w)(v - w)) & \text{if } K(v) > b, K(w) < a, \\ (a - b)/(B(v, w)(v - w)) & \text{if } K(v) < a, K(w) > b. \end{cases}$$

With this choice

$$F(v) - F(w) = P_{[a,b]}(K(v)) - P_{[a,b]}(K(w)) = L(v, w)(v - w) \quad \forall v, w \in L^2(\Omega)$$

holds true. We can now formulate the following conditions for the convergence of Algorithm 3.

Lemma 4.2. *Let u^* be the solution of the fixed-point problem (4.5) and assume that*

$$(4.13a) \quad \text{meas}\{\mathbf{x} \in \Omega : |K(u^*) - a| \leq \tau\} \rightarrow 0 \quad \text{as } \tau \rightarrow 0,$$

$$(4.13b) \quad \text{meas}\{\mathbf{x} \in \Omega : |K(u^*) - b| \leq \tau\} \rightarrow 0 \quad \text{as } \tau \rightarrow 0.$$

Furthermore we assume that (4.13) also holds for the discrete problems. Then the method described in Algorithm 3 converges for sufficiently small mesh sizes h_{\max} .

Proof. Using Corollary 5.3 of [17], it suffices to show that (4.7)-(4.9) are satisfied for F and its discretization F^h . We give the proof for the continuous operator, analogous arguments can be used for the discrete operator.

Equation (4.7) holds due to the definition of the operator L . From (4.12) it follows that the operator θ takes values only in $[0, 1]$. We show this exemplarily for the case where $K(v)(\mathbf{x}) < a$ and $K(w)(\mathbf{x}) \in [a, b]$. Here we estimate

$$\begin{aligned} 0 &\geq a - K(w)(\mathbf{x}) > a - K(w)(\mathbf{x}) + (K(v)(\mathbf{x}) - a) = K(v)(\mathbf{x}) - K(w)(\mathbf{x}) \\ &= B(v, w)(v - w)(\mathbf{x}) \\ \Rightarrow 0 &\leq (a - K(w)(\mathbf{x})) / (B(v, w)(v - w))(\mathbf{x}) < 1. \end{aligned}$$

For the other cases the proof is similar. As K is Fréchet differentiable the differential K' is bounded in a neighborhood of u^* and hence B is bounded in a neighborhood of (u^*, u^*) . As a consequence L is also bounded in that neighborhood. Therefore it remains to show that (4.9) is satisfied.

For given v, w we decompose the domain Ω into sets according to the feasibility of $K(v)$ and $K(w)$.

$$\begin{aligned} S_1 &:= \{K(u^*) < a, K(v) < a, K(w) < a\}, \\ S_2 &:= \{K(u^*) \in [a, b], K(v) \in [a, b], K(w) \in [a, b]\}, \\ S_3 &:= \{K(u^*) > b, K(v) > b, K(w) > b\}, \\ S_4 &:= \Omega \setminus (S_1 \cup S_2 \cup S_3). \end{aligned}$$

Due to the continuity of $B(\cdot, \cdot)$ the operator $L(\cdot, \cdot)$ is continuous on the sets S_1, S_2, S_3 . We therefore only have to show continuity on the set S_4 where $K(u^*)$ is projected onto a different set than $K(v)$ or $K(w)$. We start by considering the set $M \subset S_4$ given by

$$M := \{K(u^*) < a \wedge K(v) \in [a, b]\}.$$

As $B(v, w)$ is continuous from $L^2(\Omega)$ to V and $\|\theta(v, w)\|_{L^\infty} \leq 1$ for all $v, w \in L^2(\Omega)$, we can estimate

$$\begin{aligned} \|(L(v, w) - L(u^*, u^*))z\|_{L^2(M)} &= \|\theta(v, w)B(v, w)z\|_{L^2(M)} \leq \text{meas}(M)^{\frac{q-2}{2q}} \|B(v, w)z\|_{L^q} \\ &\leq C \cdot \text{meas}(M)^{\frac{q-2}{2q}} \|z\|_{L^2}, \end{aligned}$$

with $q > 2$ such that $V \hookrightarrow L^q(\Omega)$. The expression on the left hand side then goes to zero if the measure of the set M tends to zero. In order to show that this is the case, we introduce the two sets

$$\begin{aligned} M_1(\tau) &:= \{K(u^*) - a \leq -\tau, \wedge K(v) \in [a, b]\}, \\ M_2(\tau) &:= \{|K(u^*) - a| \leq \tau\} \end{aligned}$$

such that $M \subset M_1(\tau) \cup M_2(\tau)$ for all $\tau > 0$. The measure of $M_1(\tau)$ can be estimated by

$$\begin{aligned} \tau \cdot \text{meas}(M_1(\tau))^{1/2} &\leq \|K(u^*) - K(v)\|_{L^2(M_1(\tau))} = \|B(u^*, v)(u^* - v)\|_{L^2(M_1(\tau))} \\ &\leq C\|u^* - v\|_{L^2(M_1(\tau))}. \end{aligned}$$

Therefore

$$\text{meas}(M) \leq (C\frac{1}{\tau}\|u^* - v\|_{L^2})^2 + \text{meas}(M_2(\tau)) \quad \forall \tau > 0.$$

Choosing, e.g., $\tau := \|u^* - v\|_{L^2}^\rho$ with $0 < \rho < 1$ we find that $\text{meas}(M) \rightarrow 0$ if $v \rightarrow u^*$ due to (4.13a). Hence $L(v, w) \rightarrow L(u^*, u^*)$ in $L^2(M)$. Similar arguments can also be used for the sets $\{K(u^*) < a \wedge K(w) \in [a, b]\}$, $\{K(u^*) > b \wedge K(v) \in [a, b]\}$ and $\{K(u^*) > b \wedge K(w) \in [a, b]\}$. On the sets $\{K(u^*) \in [a, b] \wedge K(v) < a\}$, $\{K(u^*) \in [a, b] \wedge K(w) < a\}$, $\{K(u^*) \in [a, b] \wedge K(v) > b\}$ and $\{K(u^*) \in [a, b] \wedge K(w) > b\}$ we have the estimate

$$\begin{aligned} \|(L(v, w) - L(u^*, u^*))z\| &= \|(\theta(v, w)B(v, w) - B(u^*, u^*))z\| \\ &\leq \|\theta(v, w)(B(v, w) - B(u^*, u^*))z\| + \|(\theta(v, w) - 1)B(u^*, u^*)z\| \\ &\leq \|(B(v, w) - B(u^*, u^*))z\| + \|B(u^*, u^*)z\|. \end{aligned}$$

Using the same arguments as in the previous cases it follows that $L(v, w) \rightarrow L(u^*, u^*)$ also on these sets. Hence (4.9) is satisfied. \square

5. NUMERICAL TESTS

5.1. Examples. For the following test examples the variables are defined on the two dimensional open unit square $\Omega = (0, 1)^2$. As a prototype of the elliptic differential operator the negative Laplace-operator, discretized using a standard five-point stencil, is chosen. For all test runs the iterates are initialized by $y^0 = u^0 = p^0 \equiv 0$. The penalty parameter is initialized by $\alpha_0 = 1$ and updated by $\alpha_{k+1} = c_\alpha \alpha_k$ with $c_\alpha = 0.25$. For runs where the smoothing parameter remains constant it is chosen as $\varepsilon = \varepsilon_0 = 10^{-3}$. If ε is coupled with α , it is initialized by $\varepsilon_0 = 1$ and updated by $\varepsilon_{k+1} = (\alpha_{k+1})^{1+\delta}$ with $\delta > 0$.

Example 5.1. Lack of strict complementarity. We construct a test problem for which the active set at the solution contains a subset where strict complementarity fails to hold, i.e., where the biactive set $B := \{y^* = 0\} \cap \{\xi^* = 0\}$ has a positive measure. This situation is challenging, as the active constraint gradients at the solution are linearly dependent. We define

$$\begin{aligned} y^\dagger(\mathbf{x}_1, \mathbf{x}_2) &= \begin{cases} 160(x_1^3 - x_1^2 + 0.25x_1)(x_2^3 - x_2^2 + 0.25x_2) & \text{in } (0, 0.5) \times (0, 0.5), \\ 0 & \text{else,} \end{cases} \\ \xi^\dagger(\mathbf{x}_1, \mathbf{x}_2) &= \max(0, -2|x_1 - 0.8| - 2|x_1 x_2 - 0.3| + 0.5), \end{aligned}$$

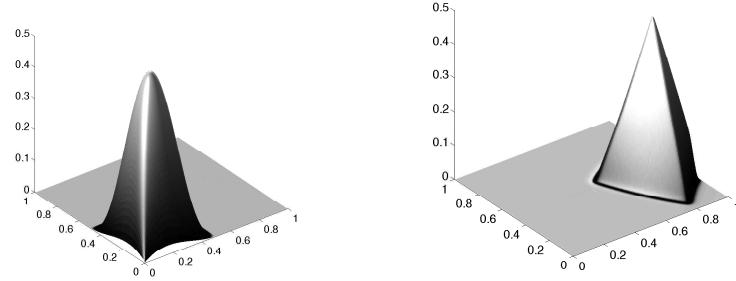


FIGURE 5.1. Optimal State y^* (left) and slack variable ξ^* (right) for Example 5.1.

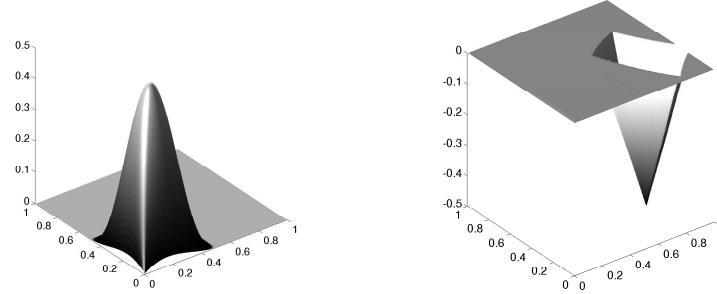


FIGURE 5.2. Adjoint state p^* (left) and multiplier λ^* (right) for Example 5.1.

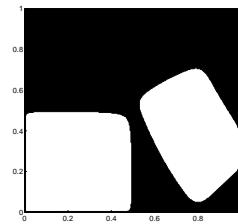


FIGURE 5.3. Biactive set (black) for Example 5.1.

and set

$$\begin{aligned} f &= -\Delta y^\dagger - y^\dagger - \xi^\dagger, \\ y_d &= y^\dagger + \xi^\dagger - \nu \Delta y^\dagger, \end{aligned}$$

with $\nu = 1$. We consider no control constraints for this test problem, i.e., $a \equiv -\infty$ and $b \equiv \infty$. The numerical solutions are displayed in Figures 5.1-5.3. Recall that for the unconstrained case the optimal control u^* is just a multiple of the adjoint state p^* , and hence not specifically depicted.

Example 5.2. Degenerate solution. For this example the optimal state y^* exhibits a very flat transition into the active set (note the scale in Figure 5.4). This makes the active set detection challenging. Purely primal active set techniques usually perform poorly in such situations. We set $\nu = 0.01$, $a = 0.01$ and $b = 0.03$.

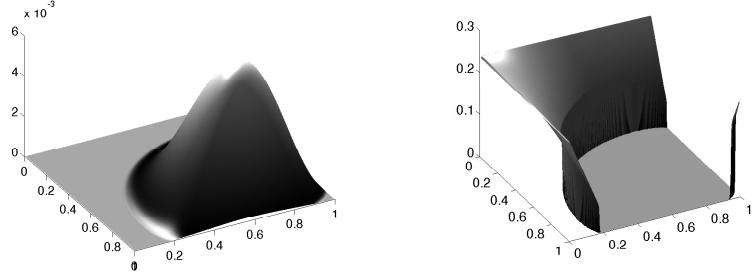


FIGURE 5.4. Optimal State y^* (left) and slack variable ξ^* (right) for Example 5.2.

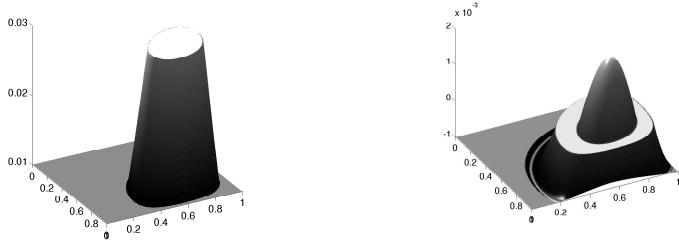


FIGURE 5.5. Optimal control u^* (left) and multiplier ϕ^* (right) for Example 5.2.

The example is defined by the data

$$f(\mathbf{x}_1, \mathbf{x}_2) = y_d(\mathbf{x}_1, \mathbf{x}_2) = -|\mathbf{x}_1 \mathbf{x}_2 - 0.5| + 0.25.$$

The numerical solution is shown in Figures 5.4- 5.6. The multiplier λ^* shows clear signs of low regularity.

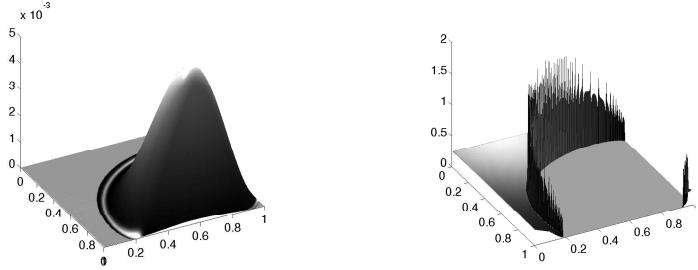


FIGURE 5.6. Adjoint state p^* (left) and multiplier λ^* (right) for Example 5.2.

5.2. Numerical Performance. Due to Theorem 3.4 the iterates of Algorithm 1 converge to an \mathcal{E} -almost C-stationary point of the MPEC. For all our test runs it could be verified, that the numerical solutions that were obtained even satisfied the stronger concept of *strong stationarity*, which was introduced in [23] for the infinite dimensional MPEC-problem (1.1).

In Table 5.2 the iteration numbers on the different grids for the FAS-multigrid method using our local and global C^1 -regularizations are displayed. The coupling of α and h described in Section 4.1.1 was used with a coarsest mesh of 15 inner grid points and a finest mesh of 255 inner grid points per dimension, respectively. Furthermore a grid dependent stopping tolerance ($tol = 0.5h^2$) was employed. The number of iterations are clearly concentrated on the coarse grids, which illustrates the efficiency of the nested iteration.

#inner gridpts.	Example 5.1		Example 5.2	
	$\max \frac{g}{\varepsilon}$	$\max \frac{l}{\varepsilon}$	$\max \frac{g}{\varepsilon}$	$\max \frac{l}{\varepsilon}$
15	6	9	5	7
31	3	3	3	2
63	3	3	3	3
127	3	3	5	3
255	2	2	2	2
total	17	20	18	17
CPU ratio FAS/MG2	0.4311	0.3738	0.2324	0.2713

TABLE 5.1. Numerical performance of the FAS-method with coupling of α and h .

For the multigrid method of second kind discussed in Section 4.1.2, the test problems were solved using the C^1 - and the C^2 -max ε -regularizations. Although the convergence analysis requires smoothness of the operator the method converged to the same solution for all regularization schemes. On each grid the required accuracy was reached, and even exceeded, after one iteration of the W-cycle. This suggest some kind of "over-solving" due to the requirement of \hat{u}^H , the exact solution of (4.6) on the respective coarser mesh.

Table 5.2 also shows the ratio between the CPU-time of the FAS-method and the multigrid method of second kind (MG2). Every Picard-iteration of MG2 requires the solution of one semilinear and one linear elliptic equation on the fine mesh, the smoothing step is therefore quite costly. This is reflected in the small CPU-ratio. The computational effort of MG2, however, can be reduced by employing an inexact version of the multigrid method of second kind, as given in [18].

5.3. Approximation properties of the outer algorithm. In order to numerically determine the approximation properties of the continuation method (Algorithm 1), the L^2 -errors $\|y_\alpha - y^*\|$ were computed for problem 5.1, where y_α is a stationary point of $(\mathcal{P}_{\alpha,\varepsilon})$ and y^* is a (strongly) stationary point of (\mathcal{P}) . The problems were solved on a fixed mesh with $h = 1/256$ for the global regularization \max_{ε}^g , once with a fixed smoothing parameter $\varepsilon = 10^{-3}$ and once with $\varepsilon = \varepsilon(\alpha) = \alpha^{1.1}$, thereby yielding $\varepsilon(\alpha)/\alpha \rightarrow 0$. Furthermore the local regularization \max_{ε}^l of the $\max(0, \cdot)$ -operator was considered with $\varepsilon = \varepsilon(\alpha) = \alpha^{1.1}$. The results are given in Figure 5.7 in a log-log-scale. The graphic suggest an approximation order of

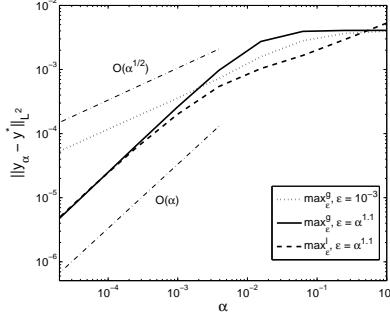


FIGURE 5.7. L^2 -errors $\|y_\alpha - y^*\|$ for problem 5.1.

$\|y_\alpha - y^*\| = \mathcal{O}(\alpha)$ if $\varepsilon(\alpha)/\alpha \rightarrow 0$ and $\|y_\alpha - y^*\| = \mathcal{O}(\alpha^{1/2})$ for fixed ε and regularization \max_{ε}^g . A similar behavior could be observed in a number of further numerical tests. In general the approximation properties for $\varepsilon(\alpha)/\alpha \rightarrow 0$ showed no significant difference for the two types of regularizations considered. Based on these observations we motivate the stopping criterion introduced in Section 4.1.1. If we assume a discretization error of order h^2 , i.e.,

$$\|y_h - y^*\|_{L^2} = \mathcal{O}(h^2),$$

where y_h is the exact solution of the discrete MPEC, as is the case for linear finite elements (see, e.g, [11]), this leads to an estimate of the form

$$\|y_{\alpha,h} - y^*\|_{L^2} = \mathcal{O}(\alpha^s + h^2).$$

Here $y_{\alpha,h}$ is the solution of the discrete version of the smoothed penalized problem $(\mathcal{P}_{\alpha,\varepsilon})$ and $s \in (0.5, 1)$ is the respective approximation order. If the smoothed penalized problem is solved on a fixed grid with mesh size h , the discretization error dominates the approximation error if $\alpha \leq h^{2/s}$.

Decreasing the penalty parameter further then leads to no improvement of the numerical solution. On a fixed grid the smoothed penalized problem is therefore

solved as long as

$$\alpha \geq Ch^{2/s},$$

where $C > 0$ is an appropriately chosen constant. This justifies (4.3). If α drops below that threshold the grid is refined, or if already on the finest mesh, the algorithm is terminated.

5.4. Stability under mesh refinement. As Theorem 3.4 proves convergence of the algorithm in a function space setting one expects that the discrete method exhibits some numerical stability under mesh refinements. For a fixed sequence $\{\alpha_k\}$ (i.e., α_k independent of h) and a fixed tolerance we therefore solved Examples 5.1 and 5.2 on different meshes, but this time neither coupling α with h , nor employing a grid dependent stopping tolerance. For the sake of a better comparison a cycle index of $\gamma = 1$ (=V-cycle) was used. Table 5.2 shows the total number of iterations for the FAS-multigrid method with the local and global C^1 -regularizations. The results imply mesh-independent behavior of the method.

TABLE 5.2. Number of iterations on the different grids for the FAS-method without coupling of α and h .

#inner gridpts.	Example 5.1		Example 5.2	
	\max_{ε}^g	\max_{ε}^l	\max_{ε}^g	\max_{ε}^l
15	20	25	23	26
31	25	29	25	27
63	25	30	26	30
127	28	31	29	29
255	28	32	27	29
511	28	32	27	30

ν	constr.		unconstr.	
	V-cyc.	W-cyc.	V-cyc.	W-cyc.
1	0.0433	0.0219	0.1217	0.0220
1e-1	0.0370	0.0238	0.1615	0.0251
1e-2	0.2777	0.0234	0.7792	0.0724

TABLE 5.3. Estimated FAS convergence factors for problem 5.1

5.5. Convergence factors for the FAS algorithm. In order to report the numerical behavior of the FAS-scheme, the optimality system (4.1) of a smoothed penalized problem with fixed parameters $\alpha = \varepsilon = 1e-3$ was solved using the FAS-method and the global C^1 -regularization of the max-operator. Both test problems were once solved using a cycle index $\gamma = 1$ (=V-cycle) and once with $\gamma = 2$, resulting in a W-cycle. Furthermore, different values for the cost parameter ν in the objective function were used.

For both test problems the control unconstrained case as well as the case with point-wise bilateral control constraints were considered. For problem 5.1 the constraints $a \equiv 0.1$, $b \equiv 0.4$ were enforced. The solution of the MPEC with these

ν	constr.		unconstr.	
	V-cyc.	W-cyc.	V-cyc.	W-cyc.
1	0.0387	0.0219	0.0389	0.0218
1e-1	0.0396	0.0217	0.0377	0.0218
1e-2	0.1312	0.0220	0.2425	0.0228

TABLE 5.4. Estimated FAS convergence factors for problem 5.2

constraints still showed a biactive set of positive measure. Note that in view of Theorem 3.4 the control constrained case immediately yields convergence of the stationary points of the smoothed penalized problems, whereas the seemingly simpler control-unconstrained case requires the additional assumption on the boundedness of $\{u_\alpha\}$ in order to guarantee convergence.

Tables 5.3-5.4 show the estimated convergence factors for the state variable y , which are defined as the asymptotic values of the ratios between the discrete H^{-1} -norms of the residuals of the state equations resulting from two successive multigrid cycles on a given mesh [9, 7].

Tables 5.3-5.4 suggest that the convergence factor depends on the cost parameter for the control ν , i.e., the condition of the problem. If the problem is solved using V-cycles this dependency is quite distinct, whereas the use of W-cycles results in a more stable behavior. Furthermore the presence of control constraints seems to have a stabilizing influence on the performance.

APPENDIX

The following results are used in this paper. The proof techniques are independent of the MPEC context, nevertheless we provide the proofs for the sake of completeness. For $v \in L^2(\Omega)$ we use the notation $v^+ := \max(0, v)$. The following lemma investigates some properties of the $\max(0, \cdot)$ -operator.

Lemma A.1. *For $\{v_\alpha\} \subset V$ and $\tilde{v} \in V$ the following assertions hold:*

- (i) *If $v_\alpha \rightharpoonup \tilde{v}$ in V , then also $v_\alpha^+ \rightharpoonup \tilde{v}^+$ in V .*
- (ii) *If $v_\alpha \rightarrow \tilde{v}$ in V , then also $v_\alpha^+ \rightarrow \tilde{v}^+$ in V .*

Proof. Due to the compact embedding of V into $L^2(\Omega)$ and the Lipschitz continuity of $\max(0, \cdot) : L^2(\Omega) \rightarrow L^2(\Omega)$ we find that v_α^+ converges to \tilde{v}^+ strongly in $L^2(\Omega)$. Furthermore for every $\alpha > 0$

$$\|\nabla v_\alpha^+\|_{L^2(\Omega)^n} \leq \|\nabla v_\alpha\|_{L^2(\Omega)^n} \leq C$$

for some $C > 0$ independent of α . Hence there exists $\eta = (\eta_1, \dots, \eta_n) \in L^2(\Omega)^n$ such that on a suitable subsequence $\frac{\partial v_\alpha^+}{\partial x_i} \rightharpoonup \eta_i$ for all $1 \leq i \leq n$. We verify that indeed $\eta = \nabla \tilde{v}^+$ by multiplying by a test function $\varphi \in C_0^\infty(\Omega)$. For every $1 \leq i \leq n$ we find that

$$(\eta_i, \varphi) = \lim_{\alpha \rightarrow 0} \left(\frac{\partial v_\alpha^+}{\partial x_i}, \varphi \right) = - \lim_{\alpha \rightarrow 0} \left(v_\alpha^+, \frac{\partial \varphi}{\partial x_i} \right) = - \left(\tilde{v}^+, \frac{\partial \varphi}{\partial x_i} \right) = \left(\frac{\partial \tilde{v}^+}{\partial x_i}, \varphi \right).$$

As the weak limit of the subsequence is uniquely determined, we find that in fact $\nabla v_\alpha^+ \rightharpoonup \nabla \tilde{v}^+$ on the whole sequence. Finally if v_α converges to \tilde{v} strongly in V

then ∇v_α converges to $\nabla \tilde{v}$ strongly in $L^2(\Omega)^n$ and strong convergence of ∇v_α^+ to $\nabla \tilde{v}^+$ in $L^2(\Omega)^n$ follows from

$$\begin{aligned}\|\nabla v_\alpha^+ - \nabla \tilde{v}^+\|_{L^2(\Omega)^n}^2 &= (\nabla v_\alpha^+, \nabla v_\alpha^+) - 2(\nabla v_\alpha^+, \nabla \tilde{v}^+) + (\nabla \tilde{v}^+, \nabla \tilde{v}^+) \\ &= (\nabla v_\alpha^+, \nabla v_\alpha) - 2(\nabla v_\alpha^+, \nabla \tilde{v}^+) + (\nabla \tilde{v}^+, \nabla \tilde{v}^+) \rightarrow 0.\end{aligned}$$

□

Optimality conditions. In this paper we use a result due to Zowe and Kurcyusz [33] to derive the first order system for the smoothed-penalized problems. For the sake of clarity we briefly recall the main result of [33]. Consider the general mathematical programming problem

$$(A.1) \quad \min_{x \in X} F(x) \quad \text{s.t. } x \in C, g(x) \in K,$$

where F is a differentiable real functional defined on a real Banach space X , C is a non-empty closed convex subset of X , g is a continuously differentiable map from X into a real Banach space Y and K is a closed convex cone in Y with vertex at the origin. For fixed $x \in X$ and $y \in Y$ let $C(x)$ and $K(y)$ denote the conical hull of $C - \{x\}$ and $K - \{y\}$, respectively, i.e.,

$$\begin{aligned}C(x) &:= \{\lambda(c - x) : c \in C, \lambda \geq 0\}, \\ K(y) &:= \{k - \lambda y : k \in K, \lambda \geq 0\}.\end{aligned}$$

The quantity $y^* \in Y^*$ is called a Lagrange multiplier of problem (A.1) at an optimal point $\bar{x} \in X$, if

$$\begin{aligned}(i) \quad &y^* \in K^+, \\ (ii) \quad &\langle y^*, g(\bar{x}) \rangle_{Y^*, Y} = 0, \\ (iii) \quad &F'(\bar{x}) - y^*(g'(\bar{x})) \in C(\bar{x})^+,\end{aligned}$$

where X^* and Y^* denote the topological duals of X and Y and for each subset M of X (or Y respectively), M^+ denotes its polar cone

$$M^+ := \{x^* \in X^* : \langle x^*, \mu \rangle_{X^*, X} \geq 0 \quad \text{for all } \mu \in M\}.$$

For an optimal point $\bar{x} \in X$ let $\Lambda(\bar{x})$ denote the set of Lagrange multipliers for problem (A.1) at \bar{x} . The main result in [33] then defines constraint qualifications that guarantee the existence of Lagrange multipliers at the optimal solution:

Theorem A.2. *Let \bar{x} be an optimal solution for problem (A.1). If*

$$(A.2) \quad g'(\bar{x})C(\bar{x}) - K(g(\bar{x})) = Y,$$

then the set $\Lambda(\bar{x})$ of Lagrange multipliers for problem (A.1) at \bar{x} is non-empty and bounded.

We derive the optimality conditions for $(\mathcal{P}_{\alpha, \varepsilon})$ by showing that the smoothed penalized problem satisfies the constraint qualification (A.2). For that purpose we introduce the admissible set for the control $U_{ad} := \{v \in L^2(\Omega) : a \leq v \leq b \text{ a.e. in } \Omega\}$ and set

$$\begin{aligned}X &:= V \times L^2(\Omega), x := (y, u), F(x) := J(y, u), \\ C &:= V \times U_{ad}, Y := V^*, K := \{0\}, \\ g(x) &:= -\mathcal{A}y + \frac{1}{\alpha} \max_\varepsilon(0, -y) + u + f.\end{aligned}$$

Now let $\bar{x} = (\bar{y}, \bar{u}) \in X$ be an optimal solution of $(\mathcal{P}_{\alpha, \varepsilon})$. As $K(g(\bar{x})) = 0$ and $\tilde{C} := V \times \{0\} \subset C(\bar{x})$, it is sufficient to show that

$$g'(\bar{x})\tilde{C} = Y,$$

which is equivalent to

$$-\left(\mathcal{A} + \frac{1}{\alpha} \max'_{\varepsilon}(0, -\bar{y})\right)V = V^*.$$

Using the Lax-Milgram Theorem we find that the constraint qualification is satisfied. Hence there exists a multiplier (adjoint state) $\bar{p} \in V$ such that

$$(A.3a) \quad \bar{y} + \mathcal{A}^*\bar{p} + \frac{1}{\alpha} \max'_{\varepsilon}(0, -\bar{y})\bar{p} = y_d,$$

$$(A.3b) \quad (\nu\bar{u} - \bar{p}, u - v) \geq 0 \quad \forall v \in U_{ad}$$

$$(A.3c) \quad \mathcal{A}\bar{y} - \frac{1}{\alpha} \max_{\varepsilon}(0, -\bar{y}) - \bar{u} = f.$$

Introducing slack variables (multipliers) $\phi^a, \phi^b \geq 0$ the variational inequality (A.3b) can be reformulated as the complementarity system given in (3.4).

REFERENCES

- [1] V. Barbu. *Optimal control of variational inequalities*, volume 100 of *Research Notes in Mathematics*. Pitman (Advanced Publishing Program), Boston, MA, 1984.
- [2] M. Bergounioux. Optimal control of an obstacle problem. *Appl. Math. Optim.*, 36(2):147–172, 1997.
- [3] M. Bergounioux. Use of augmented Lagrangian methods for the optimal control of obstacle problems. *J. Optim. Theory Appl.*, 95(1):101–126, 1997.
- [4] M. Bergounioux. Optimal control of problems governed by abstract elliptic variational inequalities with state constraints. *SIAM J. Control Optim.*, 36(1):273–289 (electronic), 1998.
- [5] M. Bergounioux and H. Dietrich. Optimal control of problems governed by obstacle type variational inequalities: a dual regularization-penalization approach. *J. Convex Anal.*, 5(2):329–351, 1998.
- [6] M. Bergounioux and F. Mignot. Optimal control of obstacle problems: existence of Lagrange multipliers. *ESAIM Control Optim. Calc. Var.*, 5:45–70 (electronic), 2000.
- [7] A. Borzì. Multigrid methods for parabolic distributed optimal control problems. *J. Comput. Appl. Math.*, 157(2):365–382, 2003.
- [8] A. Borzì. High-order discretization and multigrid solution of elliptic nonlinear constrained optimal control problems. *J. Comput. Appl. Math.*, 200(1):67–85, 2007.
- [9] A. Borzì and K. Kunisch. A multigrid scheme for elliptic constrained optimal control problems. *Comput. Optim. Appl.*, 31(3):309–333, 2005.
- [10] A. Brandt. Multi-level adaptive solutions to boundary-value problems. *Math. Comp.*, 31(138):333–390, 1977.
- [11] S. C. Brenner and L. R. Scott. *The mathematical theory of finite element methods*, volume 15 of *Texts in Applied Mathematics*. Springer-Verlag, New York, 1994.
- [12] W. L. Briggs, V. E. Henson, and S. F. McCormick. *A multigrid tutorial*. Society for Industrial and Applied Mathematics (SIAM), Philadelphia, PA, second edition, 2000.
- [13] A. Friedman. *Variational principles and free-boundary problems*. Pure and Applied Mathematics. John Wiley & Sons Inc., New York, 1982. A Wiley-Interscience Publication.
- [14] R. Glowinski, J.-L. Lions, and R. Trémolières. *Numerical analysis of variational inequalities*, volume 8 of *Studies in Mathematics and its Applications*. North-Holland Publishing Co., Amsterdam, 1981. Translated from the French.
- [15] W. Hackbusch. On the fast solutions of nonlinear elliptic equations. *Numer. Math.*, 32(1):83–95, 1979.
- [16] W. Hackbusch. On the fast solving of parabolic boundary control problems. *SIAM J. Control Optim.*, 17(2):231–244, 1979.
- [17] W. Hackbusch. Die schnelle Auflösung der Fredholmschen Integralgleichung zweiter Art. *Beiträge Numer. Math.*, 9(1):47–62, 1981.

- [18] W. Hackbusch. Error analysis of the nonlinear multigrid method of the second kind. *Apl. Mat.*, 26(1):18–29, 1981. With a loose Russian summary.
- [19] W. Hackbusch. *Multigrid methods and applications*, volume 4 of *Springer Series in Computational Mathematics*. Springer-Verlag, Berlin, 1985.
- [20] M. Hintermüller. Inverse coefficient problems for variational inequalities: optimality conditions and numerical realization. *M2AN Math. Model. Numer. Anal.*, 35(1):129–152, 2001.
- [21] M. Hintermüller. An active-set equality constrained Newton solver with feasibility restoration for inverse coefficient problems in elliptic variational inequalities. *Inverse Problems*, 24(3):034017, 23, 2008.
- [22] M. Hintermüller, K. Ito, and K. Kunisch. The primal-dual active set strategy as a semismooth Newton method. *SIAM J. Optim.*, 13(3):865–888 (electronic) (2003), 2002.
- [23] M. Hintermüller and I. Kopacka. Mathematical programs with complementarity constraints in function space: C- and strong stationarity and a path-following algorithm. Technical report, IFB-Report No. 11 (04/2008), Department of Mathematics and Scientific Computing, University of Graz.
- [24] D. Kinderlehrer and G. Stampacchia. *An introduction to variational inequalities and their applications*, volume 31 of *Classics in Applied Mathematics*. Society for Industrial and Applied Mathematics (SIAM), Philadelphia, PA, 2000. Reprint of the 1980 original.
- [25] Z.-Q. Luo, J.-S. Pang, and D. Ralph. *Mathematical programs with equilibrium constraints*. Cambridge University Press, Cambridge, 1996.
- [26] F. Mignot and J.-P. Puel. Optimal control in some variational inequalities. *SIAM J. Control Optim.*, 22(3):466–476, 1984.
- [27] P. Neittaanmaki, J. Sprekels, and D. Tiba. *Optimization of elliptic systems*. Springer Monographs in Mathematics. Springer, New York, 2006. Theory and applications.
- [28] J. Outrata, M. Kočvara, and J. Zowe. *Nonsmooth approach to optimization problems with equilibrium constraints*, volume 28 of *Nonconvex Optimization and its Applications*. Kluwer Academic Publishers, Dordrecht, 1998. Theory, applications and numerical results.
- [29] H. Scheel and S. Scholtes. Mathematical programs with complementarity constraints: stationarity, optimality, and sensitivity. *Math. Oper. Res.*, 25(1):1–22, 2000.
- [30] S. Scholtes. Convergence properties of a regularization scheme for mathematical programs with complementarity constraints. *SIAM J. Optim.*, 11(4):918–936 (electronic), 2001.
- [31] F. Tröltzsch. *Optimale Steuerung partieller Differentialgleichungen*. Vieweg-Verlag, Wiesbaden, 2005.
- [32] J. J. Ye. Necessary and sufficient optimality conditions for mathematical programs with equilibrium constraints. *J. Math. Anal. Appl.*, 307(1):350–369, 2005.
- [33] J. Zowe and S. Kurcyusz. Regularity and stability for the mathematical programming problem in Banach spaces. *Appl. Math. Optim.*, 5(1):49–62, 1979.

M. HINTERMÜLLER, HUMBOLDT-UNIVERSITY OF BERLIN, DEPARTMENT OF MATHEMATICS, UNTER DEN LINDEN 6, 10099 BERLIN, GERMANY, AND KARL-FRANZENS-UNIVERSITY OF GRAZ, DEPARTMENT OF MATHEMATICS AND SCIENTIFIC COMPUTING, HEINRICHSTRASSE 36, A-8010 GRAZ, AUSTRIA

E-mail address: michael.hintermueller@uni-graz.at

I. KOPACKA, KARL-FRANZENS-UNIVERSITY OF GRAZ, DEPARTMENT OF MATHEMATICS AND SCIENTIFIC COMPUTING, HEINRICHSTRASSE 36, A-8010 GRAZ, AUSTRIA

E-mail address: ian.kopacka@uni-graz.at