An interior-point algorithm for the minimization arising from 3D contact problems with friction

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The paper deals with a variant of the interior-point method for the minimization of strictly quadratic objective function subject to simple bounds and separable quadratic inequality constraints. Such minimizations arise from the finite element approximation of contact problems of linear elasticity with friction in three space dimensions. The main goal of the paper is the convergence analysis of the algorithm and its implementation. The optimal preconditioners for solving ill-conditioned inner linear systems are proposed. Numerical experiments illustrate the computational efficiency for large scale problems.

**Keywords:** interior-point algorithm; convergence; preconditioners; contact problems; friction

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1. Introduction

We consider the problem

$$\min_{x \in \Omega} q(x)$$

with $q(x) = \frac{1}{2} x^T A x - x^T b$ and $\Omega = \{ x \in \mathbb{R}^{3m} : x_i \geq l_i, x_{i+m}^2 + x_{i+2m}^2 \leq g_i^2, i = 1, \ldots, m \}$, where $n = 3m$, $A \in \mathbb{R}^{n \times n}$ is symmetric, positive definite, $b \in \mathbb{R}^n$, and $l_i \in \mathbb{R}$, $g_i \in \mathbb{R}_+$, $i = 1, \ldots, m$. Such minimizations arise, e.g., from the finite element approximation of contact problems of linear elasticity with friction in three space dimensions (3D) \cite{15, 17}. If the Coulomb friction law is considered, then the fixed-point approach leads to iterations given as a sequence of problems (1). There are at least three important reasons why to solve in this case also (1) by an iterative method. \textit{(i)} The requirements on the accuracy of the computed solutions to (1) are different, they increase successively. \textit{(ii)} The initial guess of the solution to (1) is known from the previous fixed-point step. \textit{(iii)} The matrix $A$ is not assembled explicitly, it is given as a product of other matrices so that only matrix-vector products with $A$ may be performed. Moreover, one can combine both iterative processes in one (inexact) loop so that the resulting algorithm may be an efficient tool for solving large scale problems.

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The problem (1) can be solved by a general method, e.g. [2, 5, 6, 28]. Nevertheless, one can expect that a specialized algorithm taking into account the particular structure of (1) will be more efficient. The first author proposed such algorithm called KPRGP (KKT-Proportioning with Reduced Gradient Projections [10, 20, 21]), in which conjugate gradient method is combined with gradient projections in an active set strategy. It extends the algorithm of Dostál and Schöberl [9, 11] originally developed for simple bound problems. The common feature of these algorithms is the theory comprising the same convergence rate that enables us to prove the scalability of methods for solving 3D contact problems without [8, 9] and with [7, 10] friction. However, the practical behavior may be different due to the difference in the finite termination property. After finding indices of simple bounds active in the solution, the simple bound problem reduces to a linear one, for which the conjugate gradient method completes the iterative process. Unfortunately, this property does not hold for the quadratic inequalities \( x_i^2 + x_{i+2m}^2 \leq g_i^2 \). Here, the algorithm seeks also positions of the pairs \((x_{i+m}, x_{i+2m})\) lying on the curved boundaries of the active circles. Therefore, ”zig-zag iterations” may be generated so that short conjugate gradient sequences alternate with projection steps changing the active set. In order to overcome this drawback, one can recommend using a strictly feasible algorithm that does not work with any active set. Its typical representative is an interior-point method. We will deal with its primal-dual variant that is usually faster and more reliable than the pure primal or pure dual methods [29] and it is also efficient when the high accuracy of the solution is needed [5].

In the paper, we develop the path-following algorithm that was proposed in [13, 27] for solving linear programming problems. The main idea consists in applying the Newton iterations to solve equations in the system of the Karush-Kuhn-Tucker (KKT) conditions to (1). Since some unknowns in the KKT system are constrained by simple bounds, the Newton steps are damped. Another key ingredient is the centering that keeps iterations deeper in the feasible region so that longer steps may be performed. The most expensive part of each iteration is the solution of an indefinite linear system. To this end, we apply methods based on the Schur complement reduction so that reduced linear systems are solved by the conjugate gradient method. As the reduced matrices are typically ill-conditioned, preconditioners are needed. Our preconditioners are optimal in the sense that condition numbers of the preconditioned matrices are bounded by a constant multiple of the condition number of A. The total efficiency is increased by a precision control terminating adaptively the inner conjugate gradient iterations.

The rest of the paper is organized as follows. In Section 2 we introduce preliminary results comprising a suitable reformulation of the KKT conditions. In Section 3, we propose the algorithm. Its convergence is proved in Section 4. The implementation of the algorithm and the spectral analysis of the preconditioners are discussed in Section 5. Finally, Section 6 summarizes results of numerical experiments and Section 7 gives comments and concluding remarks.

Let us introduce some conventions that we use through the whole paper. The symbols \( \mathcal{M}_1 \) and \( \mathcal{M}_2 \) stand for the following sets of indices: \( \mathcal{M}_1 = \{1, 2, \ldots, m\} \) and \( \mathcal{M}_2 = \{1, 2, \ldots, 2m\} \). The Euclidean norm of \( x \in \mathbb{R}^p \) is denoted by \( \|x\| = (x_1^2 + \cdots + x_p^2)^{1/2} \). The condition number of a symmetric, positive definite matrix \( M \in \mathbb{R}^{p \times p} \) is given by \( \kappa(M) = \lambda_{\text{max}}/\lambda_{\text{min}} \), where \( \lambda_{\text{max}} \) and \( \lambda_{\text{min}} \) are the smallest and the largest eigenvalue of \( M \), respectively. The symbol \( \text{diag} \) defines a diagonal matrix as follows: if \( x \in \mathbb{R}^p \) or \( X \in \mathbb{R}^{p \times p} \), the diagonal entries of \( \text{diag}(x) \in \mathbb{R}^{p \times p} \) or \( \text{diag}(X) \in \mathbb{R}^{p \times p} \) are given by \( x \) or by the diagonal entries of \( X \), respectively. By \( I \) and \( 0 \) we denote the identity and the zero matrix, respectively. Let \( L : \mathbb{R}^p \to \mathbb{R} \), \( L = L(x), x \in \mathbb{R}^p \), be a differentiable function and let \( y \) be a subset of its variables \( x \).
The symbol $\nabla_y L$ stands for the partial gradient of $L$ whose components are given by $y$.

2. Notation and preliminaries

As (1) is the minimization of the strictly quadratic objective function $q$ on the convex set $\Omega$, the solution exists and it is necessarily unique [5]. We denote it by $x^*$. Let us introduce the Lagrangian $L : \mathbb{R}^n \times \mathbb{R}^{2m} \mapsto \mathbb{R}$ associated with (1) by

$$L(x, \nu) = q(x) + \sum_{i \in M_1} \nu_i (l_i - x_i) + \sum_{i \in M_1} \nu_{i+m} (x_{i+m}^2 + x_{i+2m}^2 - g_i^2),$$

where $\nu = (\nu_1, \ldots, \nu_{2m})^\top \in \mathbb{R}^{2m}$ is the Lagrange multiplier vector to the constraints in $\Omega$. The solution $x^*$ is the first component of the saddle-point $(x^*, \nu^*) \in \mathbb{R}^n \times \mathbb{R}^{2m}$ to $L$ that is fully determined by the KKT conditions [5]:

$$\nabla_x L(x, \nu) = 0, \quad \nabla_\nu L(x, \nu) \leq 0, \quad \nu \geq 0, \quad \nu^\top \nabla_\nu L(x, \nu) = 0. \tag{2}$$

Introducing the new variable $z = -\nabla_\nu L(x, \nu)$, $z \in \mathbb{R}^{2m}$, (2) is equivalent to:

$$\nabla_x L(x, \nu) = 0, \quad \nabla_\nu L(x, \nu) + z = 0, \quad \nu^\top z = 0, \quad \nu \geq 0, \quad z \geq 0. \tag{3}$$

Let us define the function $F : \mathbb{R}^{n+4m} \mapsto \mathbb{R}^{n+4m}$ by

$$F(v) = (\nabla_x L(x, \nu)^\top, (\nabla_\nu L(x, \nu) + z)^\top, e^\top NZ)^\top,$$

where $v = (x^\top, \nu^\top, z^\top)^\top \in \mathbb{R}^{n+4m}$, $N = \text{diag}(\nu)$, $Z = \text{diag}(z)$, and $e \in \mathbb{R}^{2m}$ is the vector of all ones.

**Lemma 2.1** The solution $x^*$ to (1) is the first component of the solution $v^* = (x^*^\top, \nu^*^\top, z^*^\top)^\top$ to

$$F(v) = 0, \quad \nu \geq 0, \quad z \geq 0. \tag{4}$$

**Proof** (4) is equivalent to (3). ■

The Jacobi matrix $J = J(v)$ to $F$ at $v$ reads as follows:

$$J = \begin{pmatrix} J_{11} & J_{12} & 0 \\ J_{21} & 0 & I \\ 0 & Z & N \end{pmatrix}, \tag{5}$$

where

$$J_{11} = A + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 2N_2 & 0 \\ 0 & 0 & 2N_2 \end{pmatrix}, \quad J_{12} = J_{21}^\top = \begin{pmatrix} -I & 0 \\ 0 & 2X_2 \\ 0 & 2X_3 \end{pmatrix},$$

with $N_2 = \text{diag}(\nu_{m+1}, \ldots, \nu_{2m})$ and $X_k = \text{diag}(x_{(k-1)m+1}, \ldots, x_{km})$, $k = 2, 3$.

**Lemma 2.2** If $z > 0$, then $J = J(v)$ is non-singular for any $x$ and $\nu \geq 0$. 


The non-singularity of a matrix is guaranteed by the non-singularity of its diagonal block and the respective Schur complement [3]. The block \((0 \quad I) \quad \begin{pmatrix} Z & N \end{pmatrix}\) in \(J\) is non-singular due to \(z > 0\). The Schur complement to this block reads as \(J_{11} + J_{12}Z^{-1}NJ_{21}\). It is the positive definite matrix, since \(A\) is positive definite and \(\nu \geq 0, z > 0\).

Remark 1 The Jacobi matrix may be singular at the solution \(v^*\). This situation arises, e.g., when \(\nu_i^* = 0\) and \(z_i^* = 0\) for at least one \(i \in M_2\), since the corresponding row in \(J(v^*)\) vanishes.

Let \(v^{(k)} = (x^{(k)\top}, \nu^{(k)\top}, z^{(k)\top})\top\) with \(\nu^{(k)} > 0, z^{(k)} > 0\) be a known approximation of \(v^*\). The damped Newton method consists in computing the standard Newton direction \(\Delta v^{(k+1)}\) from the linear system given by the Jacobi matrix and, then, in defining the new iteration \(v^{(k+1)}\) in this direction using a steplength \(\alpha_k \in (0, 1]\):

\[
J(v^{(k)}) \Delta v^{(k+1)} = -F(v^{(k)}), \quad v^{(k+1)} = v^{(k)} + \alpha_k \Delta v^{(k+1)}. \tag{6}
\]

By the choice of \(\alpha_k\) one can guarantee positiveness of the components \(\nu^{(k+1)}, z^{(k+1)}\) of \(v^{(k+1)}\). Unfortunately, the computations based directly on (6) can take short steps before violating conditions \(\nu^{(k+1)} > 0, z^{(k+1)} > 0\) so that the convergence rate may be slow. In the next section we modify these iterations.

3. Algorithm

Let us replace (4) by

\[
F(v) = (0^\top, 0^\top, \tau e^\top)^\top, \quad \nu > 0, \quad z > 0, \tag{7}
\]

where \(\tau > 0\). Solutions \(v^*\) to (7) define in \(\mathbb{R}^{n+4m}\) a curve \(C(\tau)\) called the central path. This curve leads to \(v^*\), when \(\tau\) tends to zero. In the algorithm, we combine the Newton method applied to the equation in (7) with changes of \(\tau\) so that the iterations follow \(C(\tau)\). To this end, we define the neighborhood of the central path by

\[
\mathcal{N}(\gamma, \beta) = \{v = (x^\top, \nu^\top, z^\top)^\top \in \mathbb{R}^{n+4m} : \|\nabla_x L(x, \nu)\| \leq \beta \vartheta, \|\nabla_\nu L(x, \nu) + z\| \leq \beta \vartheta, \nu \geq 0, z \geq 0, \nu_i z_i \geq \gamma \vartheta, i \in M_2\}, \tag{8}
\]

where \(\beta \geq 0, \gamma \in (0, 1]\), and

\[
\vartheta = \vartheta(v) = \frac{\nu^\top z}{2m}.
\]

It is readily seen that \(\mathcal{N}(\gamma, \beta) \supseteq C(\tau)\) and \(\mathcal{N}(1, 0) = C(\tau)\).

Lemma 3.1 Let \(v \in \mathcal{N}(\gamma, \beta)\) and let either \(\nu_j = 0\) or \(z_j = 0\) for at least one \(j \in M_2\). Then \(v\) is the solution to (4).

Proof As \(\nu \geq 0\) and \(z \geq 0\), the inequality \(0 = \nu_j z_j \geq \gamma \vartheta \geq 0\) yields \(\vartheta = 0\). The remaining inequalities in the definition of \(\mathcal{N}(\gamma, \beta)\) imply \(\nabla_x L(x, \nu) = 0\) and \(\nabla_\nu L(x, \nu) + z = 0\). Therefore, (3) holds that proves the lemma.
In the $k$th iteration of the path-following (PF) algorithm, we modify $\tau$ by the product of $\vartheta_k = \vartheta(v(k))$ with the centering parameter $\sigma_k \in [\sigma_{\text{min}}, \sigma_{\text{max}}]$, $0 \leq \sigma_{\text{min}} \leq \sigma_{\text{max}} \leq 1$. The value $\sigma_k = 0$ leads to the standard Newton direction, while $\sigma_k = 1$ gives the fully centered direction. The algorithm uses also the Armijo-type condition (10) ensuring that the sequence $\{\vartheta_k\}$ is decreasing (see [29]).

Let us note that the algorithm is well-defined. Since $z(k) > 0$, Lemma 2.2 guarantees the non-singularity of the Jacobi matrix in (9). The existence of $\alpha_k$ satisfying all requirements of step (3) will be proved in Lemma 4.2. The typical values of the parameters and the choice of the initial iteration will be discussed in Section 5. The algorithm extends, in some sense, ideas used in [29] for solving linear programming problems. The main change of our implementation consists in the necessity to solve inner linear systems (9) whose spectral properties depend on the matrix $A$. Moreover, the convergence analysis requires to add the norm terms in the definition of $N(\gamma, \beta)$ and to use the Armijo-type condition (10).

### Algorithm PF

Given $\gamma \in (0, 1]$, $\beta \geq 1$, $0 < \sigma_{\text{min}} \leq \sigma_{\text{max}} \leq 1/2$, $\omega \in (0, 1)$, and $\epsilon \geq 0$. Let $v(0) \in N(\gamma, \beta)$ and set $k := 0$.

1. Choose $\sigma_k \in [\sigma_{\text{min}}, \sigma_{\text{max}}]$.
2. If $\nu(k) > 0$ and $z(k) > 0$, solve
   \begin{equation}
   J(v(k))\Delta v^{(k+1)} = -F(v(k)) + (0^T, 0^T, \sigma_k \vartheta_k e^T)^T,
   \end{equation}
   else set $\Delta v^{(k+1)} = 0$.
3. Set $v^{(k+1)} = v(k) + \alpha_k \Delta v^{(k+1)}$
   using the largest $\alpha_k \in (0, 1]$ satisfying $v^{(k+1)} \in N(\gamma, \beta)$ and
   \begin{equation}
   \vartheta_{k+1} \leq (1 - \alpha_k \omega (1 - \sigma_k)) \vartheta_k.
   \end{equation}
4. Return $\bar{v} = v^{(k+1)}$, when
   \begin{equation}
   \text{err}^{(k)} := \|v^{(k+1)} - v(k)\|/\|v^{(k+1)}\| \leq \epsilon,
   \end{equation}
   else set $k := k + 1$ and go to step (1).

Let us note that the algorithm is well-defined. Since $z(k) > 0$, Lemma 2.2 guarantees the non-singularity of the Jacobi matrix in (9). The existence of $\alpha_k$ satisfying all requirements of step (3) will be proved in Lemma 4.2. The typical values of the parameters and the choice of the initial iteration will be discussed in Section 5. The algorithm extends, in some sense, ideas used in [29] for solving linear programming problems. The main change of our implementation consists in the necessity to solve inner linear systems (9) whose spectral properties depend on the matrix $A$. Moreover, the convergence analysis requires to add the norm terms in the definition of $N(\gamma, \beta)$ and to use the Armijo-type condition (10).

### 4. Convergence analysis

To prove the convergence of Algorithm PF we modify the ideas of [26, 30], where analogous path-following algorithms are analyzed for the solution of discrete variational inequality or nonlinear complementarity problems, respectively. Our modification leads to different restrictions on the parameters of the algorithm. Moreover, we remove the lack of the analysis by adding the assumption in Theorem 4.3 on the boundedness of the sequence generated by Algorithm PF.
**Lemma 4.1** Let $v^{(k)} \in N(\gamma, \beta)$ with $z^{(k)} > 0$ and let $\Delta v^{(k+1)}$ satisfy (9). It holds:

$$z_i^{(k)} \Delta \nu_i^{(k+1)} + \nu_i^{(k)} \Delta z_i^{(k+1)} = -\nu_i^{(k)} z_i^{(k)} + \sigma_k \vartheta, \quad i \in M_2.$$ 

**Proof** Using notation introduced in (5), the third block equation in (9) reads as

$$Z^{(k)} \Delta \nu^{(k+1)} + N^{(k)} \Delta z^{(k+1)} = -N^{(k)} Z^{(k)} e + \sigma_k \vartheta e$$

that proves the lemma. □

In the next lemma, we denote by $B(\hat{v}, \hat{\delta})$ the closed ball in $\mathbb{R}^{n+4m}$ with the center at $\hat{v}$ and the radius $\hat{\delta} > 0$.

**Lemma 4.2** Let $\gamma \in (0, 1], \beta \geq 1, 0 < \sigma_{\min} \leq \sigma_{\max} \leq 1/2, \omega \in (0, 1)$, and $\hat{v} \in N(\gamma, \beta), \hat{v} \neq v^*$. There are $\hat{\delta} > 0$ and $\hat{\alpha} \in (0, 1]$ such that the steplength $\alpha_k$ in step (3°) of Algorithm PF satisfies $\alpha_k \geq \hat{\alpha}$ for any $v^{(k)} \in N(\gamma, \beta) \cap B(\hat{v}, \hat{\delta})$.

**Proof** Let us define

$$\hat{\delta} = \frac{1}{2} \min_{i \in M_2} \{\min\{\hat{\nu}_i, \hat{z}_i\}\}.$$ 

Note that $\hat{\delta} > 0$ by Lemma 2.2. For the sake of simplicity, we omit the iterative index $k$ in the proof and we denote $v(\alpha) = v + \alpha \Delta v$ that induces also notation $x(\alpha), \nu(\alpha), z(\alpha)$, and $\vartheta(\alpha) = \vartheta(v(\alpha))$. The value of $\hat{\alpha}$ will be defined successively so that we will examine lower bounds for $\alpha = \alpha_k$ given by the requirements of step (3°), i.e.:

$$\nu(\alpha), z(\alpha) \geq 0,$$ 

$$\nu_i(\alpha) z_i(\alpha) \geq \gamma \vartheta(\alpha), \quad i \in M_2,$$

$$\vartheta(\alpha) \leq (1 - \alpha \omega (1 - \sigma)) \vartheta,$$

$$\|\nabla x L(x(\alpha), \nu(\alpha))\| \leq \beta \vartheta(\alpha),$$

$$\|\nabla v L(x(\alpha), \nu(\alpha)) + z(\alpha)\| \leq \beta \vartheta(\alpha).$$

First of all we introduce some auxiliary results. The definition (12) implies $\hat{\nu}_i - \hat{\delta} \geq \hat{\delta}$ and $\hat{z}_i - \hat{\delta} \geq \hat{\delta}$ and, since $v \in B(\hat{v}, \hat{\delta})$, we get also $\hat{\nu}_i - \nu_i \leq \hat{\delta}, \hat{z}_i - z_i \leq \hat{\delta}$. Therefore,

$$\nu_i z_i \geq (\hat{\nu}_i - \hat{\delta})(\hat{z}_i - \hat{\delta}) \geq \hat{\delta}^2, \quad i \in M_2,$$

and, consequently,

$$\vartheta \geq \hat{\delta}^2.$$ 

As $\delta > 0$ by (18), the Jacobi matrix $J(v)$ is non-singular by Lemma 2.2 and its inversion as well as the right-hand side in (9) are the continuous functions on $B(\hat{v}, \hat{\delta})$. Thus, there is a constant $C > 0$ such that

$$\|\Delta v\| \leq C$$

for all $v \in B(\hat{v}, \hat{\delta})$ and $\sigma \in [\sigma_{\min}, \sigma_{\max}]$. Recall that due to definition (8), it holds

$$\nu_i z_i \geq \gamma \vartheta, \quad i \in M_2.$$ 

(21)
Using Lemma 4.1, we obtain
\[
\nu_i(\alpha)z_i(\alpha) = \nu_i z_i + \alpha(z_i \Delta \nu_i + \nu_i \Delta z_i) + \alpha^2 \Delta \nu_i \Delta z_i
\]
\[
= (1 - \alpha)\nu_i z_i + \alpha \sigma \vartheta + \alpha^2 \Delta \nu_i \Delta z_i
\]
(22)
that gives \(\nu(\alpha)\top z(\alpha) = (1 - \alpha)\nu\top z + \alpha \sigma \nu\top z + \alpha^2 \Delta \nu\top \Delta z\). By the Cauchy–Schwarz inequality and (20), we arrive at
\[
(1 - \alpha)\nu\top z + \alpha \sigma \nu\top z - \alpha^2 C^2 \leq \nu(\alpha)\top z(\alpha) \leq (1 - \alpha)\nu\top z + \alpha \sigma \nu\top z + \alpha^2 C^2
\]
(23)
and
\[
(1 - \alpha)\vartheta + \alpha \sigma \vartheta - \alpha^2 C^2 \frac{2}{2m} \leq \vartheta(\alpha) \leq (1 - \alpha)\vartheta + \alpha \sigma \vartheta + \alpha^2 C^2 \frac{2}{2m}
\]
(24)
Note that (20) yields also \(-C \leq \Delta \nu_i \leq C\) and \(-C \leq \Delta z_i \leq C\). Therefore, (22) and (21) imply
\[
\nu_i(\alpha)z_i(\alpha) \geq (1 - \alpha)\gamma \vartheta + \alpha \sigma \vartheta - \alpha^2 C^2.
\]
(25)
Let us define \(\hat{\alpha}_1 = \min\{1, \delta/(2C)\}\) and let \(\alpha \in (0, \hat{\alpha}_1]\). Using \(\nu_i \geq \hat{\nu}_i - \hat{\delta} \geq \hat{\delta}\) and (20), we get
\[
\nu_i(\alpha) = \nu_i + \alpha \Delta \nu_i \geq \hat{\delta} - \frac{\hat{\delta}}{2C} \Delta \nu_i \geq \frac{\hat{\delta}}{2} > 0, \quad i \in M_2.
\]
Since the same bound holds for \(z_i(\alpha)\), the inequalities (13) are satisfied.

Further, let us define \(\hat{\alpha}_2 = \min\{\hat{\alpha}_1, \sigma_{\min}(1 - \gamma)\hat{\delta}^2/(2C^2)\}\) and let \(\alpha \in (0, \hat{\alpha}_2]\). Then \(\alpha^2 \leq \alpha \sigma(1 - \gamma)\vartheta/(2C^2)\) due to (19) so that
\[
\alpha \sigma \vartheta - \alpha^2 C^2 \geq \alpha \sigma \gamma \vartheta + \alpha^2 C^2 \geq \alpha \sigma \gamma \vartheta + \alpha^2 C^2 \frac{C^2}{2m}.
\]
Using this result and the right inequality (24) in (25), we get
\[
\nu_i(\alpha)z_i(\alpha) \geq (1 - \alpha)\gamma \vartheta + \alpha \sigma \gamma \vartheta + \alpha^2 \gamma C^2 \frac{2}{m} \geq \gamma \vartheta(\alpha), \quad i \in M_2.
\]
We have proved (14).

Let us consider \(\alpha \in (0, \hat{\alpha}_3]\) with \(\hat{\alpha}_3 = \min\{\hat{\alpha}_2, m(1 - \omega)\hat{\delta}^2/C^2\}\). Then \(\alpha^2 C^2 = \alpha(\alpha C^2) \leq am(1 - \omega)\hat{\delta}^2\) together with (19) and \(\sigma \leq 1/2\) give
\[
\alpha^2 C^2 \leq am(1 - \omega)\vartheta = a(1 - \omega)\frac{\nu\top z}{2} \leq a(1 - \omega)(1 - \sigma)\nu\top z.
\]
Applying this result in (23), we arrive at
\[
\nu(\alpha)\top z(\alpha) \leq \nu\top z - \alpha(1 - \sigma)\nu\top z + \alpha^2 C^2 \leq [1 - \omega(1 - \sigma)]\nu\top z
\]
(26)
that proves (15).

It remains to show when the conditions (16) and (17) are satisfied. For convenience, we denote \(r_x(x, \nu) = \nabla_x L(x, \nu)\) and \(r_\nu(x, z) = \nabla_\nu L(x, \nu) + z\).
Let us consider \( \alpha \in (0, \bar{\alpha}_4) \) with \( \bar{\alpha}_4 = \min\{\hat{\alpha}_3, \sigma_{\text{min}} \delta^2/(3C^2)\} \). Using (19), we get
\[
\sigma \vartheta - \frac{\alpha^2 C^2}{2m} - 2\alpha C^2 \geq \sigma \vartheta - 3\alpha C^2 \geq \sigma \vartheta - \sigma_{\text{min}} \delta^2 \geq 0.
\] (27)

We split \( r_x \) on three components of the same length \( m \), i.e., \( r_x = (r^T_{x_1}, r^T_{x_2}, r^T_{x_3})^T \).

It is easily seen from the definition of \( L \) that \( r_{x_1} \) is the linear function while \( r_{x_2} \)
and \( r_{x_3} \) are the non-linear functions. Therefore, the Taylor expansion of \( r_x \) reads
as follows:
\[
\begin{align*}
n_x(x(\alpha), \nu(\alpha)) &= r_x(x, \nu) + \alpha (\nabla_x r_x(x, \nu) \Delta x + \nabla_\nu r_x(x, \nu) \Delta \nu) + \frac{\alpha^2}{2} s_x(\Delta x, \Delta \nu) \\

\text{(28)}
\end{align*}
\]
with \( s_x = (s^T_{x_1}, s^T_{x_2}, s^T_{x_3})^T \), where \( s_{x_1} = 0 \) and \( s_{x_2,j}(\Delta x, \Delta \nu) = 4\Delta x_j + (k-1)m \Delta \nu_{j+m}, \)
\( k = 2, 3, j \in M_1 \). Since (20) implies the boundness of \( \Delta x \) and the components of \( \Delta \nu \) by \( C \), it holds:
\[
\begin{align*}
\|s_x(\Delta x, \Delta \nu)\| &= \sum_{j \in M_1} ((4\Delta x_{j+m} \Delta \nu_{j+m})^2 + (4\Delta x_{j+2m} \Delta \nu_{j+m})^2) \\

&\leq 16 \max_{i \in M_1} \{(\Delta \nu_{i+m})^2\} \sum_{j \in M_1} ((\Delta x_{j+m})^2 + (\Delta x_{j+2m})^2) \\

&\leq 16 C^2 \|\Delta x\| \leq 16 C^4. \quad (29)
\end{align*}
\]

From the linear system (9), one can see that \( \nabla_x r_x(x, \nu) \Delta x + \nabla_\nu r_x(x, \nu) \Delta \nu = -r_x(x, \nu) \). Substituting in (28) and using the norm, we get
\[
\|r_x(x(\alpha), \nu(\alpha))\| \leq (1 - \alpha)\|r_x(x, \nu)\| + \frac{\alpha^2}{2} \|s_x(\Delta x, \Delta \nu)\|.
\]

The definition (8) and (29) yield
\[
\|r_x(x(\alpha), \nu(\alpha))\| \leq (1 - \alpha)\beta \vartheta + 2\alpha^2 C^2. \quad (30)
\]

The left inequality (24) implies
\[
(1 - \alpha) \vartheta \leq \vartheta(\alpha) - \alpha \sigma \vartheta + \frac{\alpha^2 C^2}{2m}. \quad (31)
\]

Using this result and the assumption \( \beta \geq 1 \) in (30), we arrive at
\[
\|r_x(x(\alpha), \nu(\alpha))\| \leq \beta \vartheta(\alpha) - \beta \alpha \sigma \vartheta - \frac{\alpha^2 C^2}{2m} - 2\alpha C^2.
\]

Finally, (27) implies \( \|r_x(x(\alpha), \nu(\alpha))\| \leq \beta \vartheta(\alpha) \) that proves (16).

The proof of (17) is analogous. We split \( r_\nu \) on two components of the same length \( m \), i.e., \( r_\nu = (r^T_{\nu_1}, r^T_{\nu_2})^T \). As for \( r_x(x, \nu) \), we derive
\[
\|r_\nu(x(\alpha), z(\alpha))\| \leq (1 - \alpha)\beta \vartheta + \frac{\alpha^2}{2} \|s_\nu(\Delta x, \Delta z)\|, \quad (32)
\]
where \( s_{\nu} = (s_{\nu_1}, s_{\nu_2})^T \) is the quadratic term from the Taylor expansion of \( r_\nu \) with the components \( s_{\nu_1} = 0 \) and \( s_{\nu_2,j}(\Delta x, \Delta z) = 2(\Delta x_{j+m})^2 + 2(\Delta x_{j+2m})^2, j \in M_1. \)

Using (20), we get
\[
\|s_{\nu}(\Delta x, \Delta z)\|^2 = \sum_{j \in M_1} \left(2(\Delta x_{j+m})^2 + 2(\Delta x_{j+2m})^2\right)^2 \leq 4 \max_{i \in M_1} \left\{((\Delta x_{i+1})^2, (\Delta x_{i+2m})^2)\right\} \sum_{j \in M_1} (|\Delta x_{j+m}| + |\Delta x_{j+2m}|)^2 \leq 4C^2 \left(\sum_{j \in M_1} (\Delta x_{j+m})^2 + 2 \sum_{j \in M_1} |\Delta x_{j+m}| |\Delta x_{j+2m}| + \sum_{j \in M_1} (\Delta x_{j+2m})^2\right) \leq 4C^2 (\|\Delta x\|^2 + 2\|\Delta x\|\|\Delta x\| + \|\Delta x\|^2) \leq 16C^4.
\] (33)

The rest of the proof uses (31), (32), and (33) analogously as in the case (16). We obtain that (17) holds for \( \alpha \in B \).

Theorem 4.3 Let \( \gamma \in (0, 1), \beta \geq 1, 0 < \sigma_{\text{min}} \leq \sigma_{\text{max}} \leq 1/2, \omega \in (0, 1), \) and \( \epsilon = 0. \) Let the sequence \( \{v^{(k)}\} \) generated by Algorithm PF be bounded. Then, either \( \{v^{(k)}\} \) is finite and its last element \( \bar{v} \) is the solution to (4), or the limit point of \( \{v^{(k)}\} \) is the solution to (4).

Proof The algorithm terminates finitely, if at least one entry of \( z^{(k)} \) vanishes for any \( k \geq 0. \) Then, Lemma 3.1 implies \( \bar{v} = v^* \).

Let us assume that the sequence \( \{v^{(k)}\} \) is infinite and consider its accumulation point \( \hat{v} \in \mathcal{N}(\gamma, \beta). \) Let us suppose for contradiction that \( \hat{v} \neq v^* \). Then Lemma 3.1 yields \( \hat{v} > 0, \hat{z} > 0 \) so that \( \hat{v} = \hat{v}^T \hat{z} / (2m) > 0. \) Recall that the \((k+1)\)th iteration satisfies
\[
\hat{v}_{k+1} \leq \hat{v}_k - \alpha_k \omega (1 - \sigma_k) \hat{v}_k.
\] (34)

Since \( \{\hat{v}_k\} \) is monotonically decreasing, we obtain
\[
\hat{v}_k \geq \hat{v} > 0, \quad k \in \mathbb{N}.
\] (35)

Denote by \( \mathcal{I} \) an infinite subsequence of \( \mathbb{N} \) such that \( v^{(k)} \to \hat{v} \) for \( k \to +\infty \) and \( k \in \mathcal{I}. \)

By Lemma 4.2, there is \( \hat{\alpha} \in [0, 1] \) such that \( \alpha_k \geq \hat{\alpha} \) for \( k \in \mathcal{I} \) sufficiently large. Using this bound in (34) together with \( \sigma_k \leq 1/2 \) and (35), we get \( \hat{v}_{k+1} \leq \hat{v}_k - \hat{\alpha} \omega \hat{v} / 2. \)

Here, \( \hat{\alpha} \omega \hat{v} / 2 \) is the positive constant independent of \( k. \) Since \( \mathcal{I} \) is infinite and \( \{\hat{v}_k\} \) is monotonically decreasing, we arrive at \( \hat{v}_k \searrow -\infty. \) This result contradicts (35) that completes the proof.

5. Implementation

In this section we describe the implementation of Algorithm PF for solving large scale problems.
5.1. Inner solvers

The computational efficiency consists in the way how the inner linear systems (9) are solved. Here, we omit the iterative index \( k \) for simplicity. Then, (9) reads as follows:

\[
\begin{pmatrix}
J_{11} & J_{12} & 0 \\
J_{21} & 0 & I \\
0 & Z & N
\end{pmatrix}
\begin{pmatrix}
\Delta x \\
\Delta \nu \\
\Delta z
\end{pmatrix}
=
\begin{pmatrix}
r_1 \\
r_2 \\
r_3
\end{pmatrix},
\]

(36)

where \( r_1 \in \mathbb{R}^n, r_2, r_3 \in \mathbb{R}^{2m} \) stand for the components of the right-hand side vector in (9). We present two solution methods both based on the Schur complement reduction [3]. The first one uses the symmetric, positive definite normal matrix

\[
J_{SC} = J_{11} + J_{12}D_{22}^{-1}J_{21},
\]

where \( D_{22} = N^{-1}Z \). It arises from (36) when the unknowns \( \Delta \nu \) and \( \Delta z \) are eliminated by

\[
\begin{pmatrix}
\Delta \nu \\
\Delta z
\end{pmatrix}
=
\begin{pmatrix}
-D_{22}^{-1}Z^{-1} \\
I & 0
\end{pmatrix}
\begin{pmatrix}
r_2 \\
r_3
\end{pmatrix}
-
\begin{pmatrix}
J_{21} \\
0
\end{pmatrix}
\Delta x.
\]

(37)

The reduced system for the unknown \( \Delta x \) reads as follows:

\[
J_{SC}\Delta x = r_1 - J_{12}(Z^{-1}r_3 - D_{22}^{-1}r_2).
\]

(38)

The second solution method is based on the augmented matrix \( J_{AM} = J_{AM}(v) \) given by

\[
J_{AM} = \begin{pmatrix}
J_{11} & J_{12} \\
J_{21} & -D_{22}
\end{pmatrix}.
\]

It arises from (36) by eliminating the unknown \( \Delta z \) using

\[
\Delta z = N^{-1}r_3 - D_{22}\Delta \nu.
\]

(39)

The reduced system in terms of \( \Delta x \) and \( \Delta \nu \) reads as follows:

\[
J_{AM}\begin{pmatrix}
\Delta x \\
\Delta \nu
\end{pmatrix} = \begin{pmatrix}
r_1 \\
r_2 - N^{-1}r_3
\end{pmatrix}.
\]

(40)

Note that \( J_{AM} \) is symmetric but indefinite and that \( J_{SC} \) is the Schur complement to the (2,2)-block in \( J_{AM} \).

To get the solution to (36), we proceed in two steps: first we solve (38) or (40) after that we compute remaining components of the solution using (37) or (39), respectively. For solving (38) and (40), we apply the conjugate gradient method. It is known that this method requires a symmetric, positive definite matrix and that its convergence rate depends on its condition number [12]. In order to guarantee convergence for the augmented matrix, we will use the indefinite preconditioner

\[
P_{AM} = \begin{pmatrix}
D_{11} & J_{12} \\
J_{21} & -D_{22}
\end{pmatrix},
\]
where $D_{11} = \text{diag}(J_{11})$. The Schur complement $P_{SC}$ to the $(2,2)$-block in $P_{AM}$, i.e.,

$$P_{SC} = D_{11} + J_{12}D_{22}^{-1}J_{21},$$

will be used as the preconditioner for $J_{SC}$. Actions of $P_{AM}^{-1}$ and $P_{SC}^{-1}$ on vectors are easily computable, since the preconditioners are defined by diagonal blocks.

**Theorem 5.1** The eigenvalues $\lambda$ of $P_{AM}^{-1}J_{AM}$ are positive. The eigenvalue $\lambda = 1$ is of the multiplicity $2m$ and the remaining $n$ eigenvalues are the same as the eigenvalues of $P_{SC}^{-1}J_{SC}$.

**Proof** The eigenvalues of $P_{AM}^{-1}J_{AM}$ can be found through the generalized eigenvalue problem:

$$
\begin{pmatrix}
J_{11} & J_{12} \\
J_{21} - D_{22}
\end{pmatrix}
\begin{pmatrix}
x \\
\nu
\end{pmatrix} = \lambda
\begin{pmatrix}
D_{11} & J_{12} \\
J_{21} - D_{22}
\end{pmatrix}
\begin{pmatrix}
x \\
\nu
\end{pmatrix}.
$$

(41)

The second block equation in (41) is satisfied, when either $\lambda = 1$ or $J_{21}x - D_{22}\nu = 0$. (i) If $\lambda = 1$, then the first block equation in (41) reduces to $J_{11}x = D_{11}x$ that holds for $x = 0$ so that $(0^\top, \nu^\top)^\top$ is the eigenvector for any $\nu \neq 0$. Let $e_i$ denote the $i$th column of the identity matrix $I \in \mathbb{R}^{2m \times 2m}$. Then $(0^\top, e_i^\top)^\top$, $i \in M_2$, are linearly independent eigenvectors associated with $\lambda = 1$. (ii) Substituting $\nu = D_{22}^{-1}J_{21}x$ in the first block equation in (41), we get

$$J_{SC}x = \lambda P_{SC}x$$

(42)

so that $\lambda$ is the eigenvalue of $P_{SC}^{-1}J_{SC}$. Since $P_{SC}$ is symmetric, positive definite as well as $J_{SC}$, the eigenvalue $\bar{\lambda} = (x^\top J_{SC}x)/(x^\top P_{SC}x)$, $x \neq 0$, is positive. The theorem is proved.

**Corollary 5.2** It follows immediately from the last theorem that

$$
\kappa(P_{SC}^{-1}J_{SC}) \leq \kappa(P_{AM}^{-1}J_{AM}).
$$

Note that $J_{SC}(v)$ and $J_{AM}(v)$ are typically ill-conditioned, when $v = \nu^{(k)}$ is sufficiently close to $v^\ast$. The reason is that the diagonal entry of $D_{22}$ or $D_{22}^{-1}$ tends to infinity, when the corresponding $\nu_i^\ast = 0$, $z_i^\ast \neq 0$ or $\nu_i^\ast \neq 0$, $z_i^\ast = 0$, respectively. Moreover, if $\nu_i^\ast = 0$, $z_i^\ast = 0$, then the matrices in (36) converge to the singular matrix $J(v^\ast)$ due to Remark 1. We prove that the condition numbers of the preconditioned matrices are bounded independently on $v = \nu^{(k)}$. To this end, we denote $B = J_{11} - A + J_{12}D_{22}^{-1}J_{21}$ and $D = \text{diag}(A)$. The generalized eigenvalue problem (42) reads as $(A + B)x = \lambda(D + B)x$ and, therefore, $\lambda$ is given by the generalized Rayleigh quotient as

$$
\lambda = \frac{x^\top Ax + x^\top Bx}{x^\top Dx + x^\top Bx}, \quad \|x\| = 1.
$$

(43)

To get bounds on $\lambda$, we will analyze the right-hand side of $\lambda$ in (43). Let $a_{\min}$ and $a_{\max}$, $0 < a_{\min} \leq a_{\max}$, be the smallest and the largest eigenvalues of $A$, respectively, so that $a_{\min} \leq x^\top Ax \leq a_{\max}$. Further, let $d_{\min} = \min_{i}\{a_{ii}\}$ and $d_{\max} = \max_{i}\{a_{ii}\}$, $0 < d_{\min} \leq d_{\max}$, be the smallest and the largest eigenvalues of $D$, respectively, so that $d_{\min} \leq x^\top Dx \leq d_{\max}$. Here, $a_{ii}$ denote the diagonal entries of $A$. Finally, note that $B$ is symmetric, positive semidefinite so that $0 \leq x^\top Bx < +\infty$. 

Theorem 5.3 All eigenvalues \( \lambda \) of the preconditioned normal matrix \( P^{-1}_{SC} J_{SC} \) lay in the interval \([a_{\min}d_{\max}^{-1}, a_{\max}d_{\min}^{-1}]\).

Proof Denote in (43) \( a = x^\top Ax \), \( b = x^\top Bx \), and \( d = x^\top Dx \) so that \( \lambda = \lambda(b; a, d) \), where

\[
\lambda(b; a, d) = \frac{a + b}{d + b} = 1 + \frac{a - d}{d + b}.
\]

Here, \( \lambda(b; a, d) \) can be considered as the hyperbola for the variable \( b \in \mathbb{R}_+ \) given by the parameters \( a \) and \( d \) satisfying \( a_{\min} \leq a \leq a_{\max} \) and \( d_{\min} \leq d \leq d_{\max} \), respectively. If \( ad^{-1} > 1 \) or \( ad^{-1} < 1 \), then the hyperbola is decreasing or increasing on \( \mathbb{R}_+ \), respectively, and, if \( ad^{-1} = 1 \), then it reduces to the constant \( "1" \). There are two extremal hyperbolas \( \lambda_{\min}(b) = \lambda(b; a_{\min}, d_{\max}) \) and \( \lambda_{\max}(b) = \lambda(b; a_{\max}, d_{\min}) \), for which

\[
\inf_{b \in \mathbb{R}_+} \lambda_{\min}(b) \leq \lambda \leq \sup_{b \in \mathbb{R}_+} \lambda_{\max}(b),
\]

(44)

Since \( a_{\min} \leq d_{\min} \), we obtain \( 1 \geq a_{\min}d_{\max}^{-1} \geq a_{\min}d_{\max}^{-1} \). Therefore, \( \lambda_{\min}(b) \) is increasing or constant on \( \mathbb{R}_+ \) so that

\[
\inf_{b \in \mathbb{R}_+} \lambda_{\min}(b) = \lambda_{\min}(0) = a_{\min}d_{\max}^{-1}.
\]

Since \( a_{\max} \geq d_{\max} \), we get \( 1 \leq a_{\max}d_{\max}^{-1} \leq a_{\max}d_{\min}^{-1} \). Therefore, \( \lambda_{\max}(b) \) is decreasing or constant on \( \mathbb{R}_+ \) so that

\[
\sup_{b \in \mathbb{R}_+} \lambda_{\max}(b) = \lambda_{\max}(0) = a_{\max}d_{\min}^{-1}.
\]

The theorem is proved.

Corollary 5.4 The theorem implies

\[
\kappa(P^{-1}_{SC} J_{SC}) \leq \frac{a_{\max}d_{\max}}{a_{\min}d_{\min}} = \kappa(A)\kappa(D).
\]

Using Theorem 5.1 and the fact that \( a_{\min}d_{\max}^{-1} \leq 1 \leq a_{\max}d_{\min}^{-1} \), we get the same result also for the preconditioned augmented matrix, i.e.,

\[
\kappa(P^{-1}_{AM} J_{AM}) \leq \kappa(A)\kappa(D).
\]

Note that \( \kappa(A)\kappa(D) \leq \kappa(A)^2 \) gives simpler but usually more pessimistic bounds.

For an alternative analysis of preconditioners in the interior-point methods we refer to [4, 24].

5.2. Implementation details

In this section we discuss, among others, the choice of the parameters in Algorithm PF. Their optimal values was found by large numerical tests that are not included in the paper. For that, we used the benchmarks of Section 6 arising from finite element approximations and, as we observed comparable behaviors of the
computations for various meshes, it seems that the optimal values of the parameters do not depend on the size of the problem.

5.2.1. Adaptive inner precision control

To increase the efficiency, we initialize the conjugate gradient method in the kth iteration of Algorithm PF by the result obtained in the previous iteration and we stop it by the adaptive precision control $\epsilon_{cgm} = \epsilon_{cgm}^{(k)} \times \|r^{(k)}\|$, where $r^{(k)}$ stands for the right-hand side vector in (38) or (40). The value $\epsilon_{cgm}^{(k)}$ is proportional to the current outer precision $\epsilon^{(k-1)}$ defined in (11) or, if the progress is not sufficient, to the improved inner tolerance $\epsilon_{cgm}^{(k-1)}$ from the previous step:

$$
\epsilon_{cgm}^{(k)} = \min\{r_{tol} \times \epsilon^{(k-1)}, c_{fact} \times \epsilon_{cgm}^{(k-1)}\},
$$

where $0 < r_{tol} < 1$, $0 < c_{fact} < 1$, $\epsilon^{(k-1)} = 1$, and $\epsilon_{cgm}^{(k-1)} = r_{tol} / c_{fact}$. Note that the computational experience showed that the initialization of the conjugate gradient method from the zero vectors is less beneficial.

5.2.2. Adaptive centering

The value $\sigma_k \in [\sigma_{\min}, \sigma_{\max}]$ is chosen by the following adaptive strategy:

$$
\sigma_k = \min\{\sigma_{\max}, \max\{\sigma_{\min}, c_\sigma \times ((1 - \xi_k) / \xi_k)^3\}\},
$$

where $\xi_k = \min_{i \in M_2} \nu_i^{(k)} / \vartheta_k$ and $c_\sigma > 0$. Notice that $\xi_k \in [\gamma, 1]$, since $\nu_i^{(k)} / \vartheta_k \geq \gamma \vartheta_k$. The value $\xi_k = 1$ implies $\nu_i^{(k)} / \vartheta_k$ for all $i \in M_2$ indicating that the current iteration $u^{(k)}$ lies near the central path. In this case, (46) gives $\sigma_k = \sigma_{\min}$ so that the computed direction is centered modestly. Oppositely, if $\xi_k = \gamma$, then $u^{(k)}$ lies on the boundary of $\mathcal{N}(\gamma, \beta)$ and $\sigma_k > \sigma_{\min}$ so that the centering is more distinctive. The critical value of $\xi_k$, for which (46) gives $\sigma_k = \sigma_{\max}$, is $\xi_k^{crit} = 1 / (1 + \sqrt{\sigma_{\max} / c_\sigma})$. In our computations, we use $\sigma_{\min} = 10^{-30}$, $\sigma_{\max} = 0.5$, and $c_\sigma = 1.25 \times 10^{-3}$ (resulting in $\xi_k^{crit} \approx 0.0284$). See [25] for more details.

5.2.3. Steplength

The steplength $\alpha = \alpha_k$ in step (3°) of Algorithm PF must satisfy five inequalities (13)-(17) for $v = u^{(k)}$. To determine $\alpha_k$, we use the backtracking procedure:

(a) Initialize $\rho \in (0, 1)$, $\alpha_k^0 \in (0, 1]$, and $j := 0$.
(b) While $ineq(\alpha_j^k)$ does not hold, set $\alpha_j^{k+1} = \rho \alpha_j^k$, $j := j + 1$ and repeat.
(c) Return $\alpha_k = \alpha_j^k$.

The initial value $\alpha_k^0$ is determined by

$$
\alpha_k^0 = \min_{\Delta \nu_i^{(k+1)} \Delta z_i^{(k+1)} < 0} \left\{1, -\delta \nu_i^{(k)} / \Delta \nu_i^{(k+1)}, -\delta z_i^{(k)} / \Delta z_i^{(k+1)}\right\}
$$

with $\delta \in (0, 1)$. It guarantees $\nu(\alpha_j^k) > 0$, $z(\alpha_j^k) > 0$ for $j \geq 0$ so that (13) holds. The satisfaction of (14)-(17) is achieved by inserting the respective inequality in the backtracking loop (b) as $ineq(\alpha_j^k)$. We consider different values of $\rho$: first we check (14) with $\rho_1$, then (15) with $\rho_2$, and finally (16) and (17) with $\rho_3$. The finite termination of the backtracking loop follows from Lemma 4.2. In the numerical experiments, we take $\delta = 0.999$, $\rho_1 = 0.9$, and $\rho_3 = 0.5$.  

An interior-point algorithm for 3D contact problems with friction
5.2.4. Parameter $\omega$

The parameter $\omega \in (0, 1)$ in the Armijo-type condition (10) realizes certain compromise between the steplength $\alpha_k$ and the decrease in $\{\theta_k\}$. The value of $\omega$ close to one may result in short $\alpha_k$ while $\omega$ close to zero may lead to slow decrease between $\theta_k$ and $\theta_{k+1}$. The numerical experiments showed that $\omega = 0.1$ gives the satisfactory behavior of Algorithm PF for our problems.

5.2.5. Initial iteration

We describe how to ensure that the initial iteration $\nu^{(0)} = (x^{(0)} \top, \nu^{(0)} \top, z^{(0)} \top) \top$ belongs to $\mathcal{N}(\gamma, \beta)$. We choose $x^{(0)} \in \mathbb{R}^n$ arbitrarily, e.g., $x^{(0)} = 0$. The vectors $\nu^{(0)} \in \mathbb{R}^{2m}$ and $z^{(0)} \in \mathbb{R}^{2m}$ are defined by $\nu^{(0)} = c_\nu e$ and $z^{(0)} = c_z e$, where $c_\nu$ and $c_z$ are given positive constants, respectively. It is easily seen that $\nu^{(0)}_i c^{(0)}_i = c_\nu c_z \geq \gamma c_\nu c_z = \gamma \theta_0$ for all $i \in \mathcal{M}_2$ and for any $\gamma \in (0, 1]$. Therefore, no restriction on $\gamma$ is necessary. The value of $\beta$ is adapted with respect to the initial iteration. First we compute

$$\bar{\beta} = \beta_0 \times \max \{\|\nabla_x L(x^{(0)}, \nu^{(0)})\|/\theta_0, \|\nabla_\nu L(x^{(0)}, \nu^{(0)}) + z^{(0)}\|/\theta_0\}$$

for given $\beta_0 \geq 1$. As Theorem 4.3 requires $\beta \geq 1$, we take $\beta = \max \{1, \bar{\beta}\}$. Note that large values of $\beta$ lead to saving in computations, since the backtracking steps for the time consuming conditions (16) and (17) may be avoided. We use $c_\nu = c_z = 1$, $\gamma = 0.001$, and $\beta_0 = 10^9$.

6. Numerical experiments

Numerical experiments will illustrate behavior of Algorithm PF for two model problems. The first one was used in [21] for testing the active set KPRGP algorithm. Its difficultness consists in the fact that the solution is almost degenerate. The second one is the contact problem of linear elasticity with Tresca friction whose finite element approximation leads to (1) [15, 17]. Moreover, we extend Algorithm PF for solving contact problems with Coulomb friction. All computations are performed in MATLAB on PC Core i7(2.8 GHz) with 4GB RAM.

In tables below we report the number $\text{iter}$ of outer iterations, the number $n_A$ of matrix-vector multiplications by $A$, and the solution time in seconds. As the multiplication by $A$ is usually the most expensive operation, the value $n_A$ determines the total complexity of computations. In labeling of columns $\text{PF}(\nu_{tol}, c_{fact})$, we introduce the values of $\nu_{tol}$ and $c_{fact}$. In order to compare the efficiency with KPRGP, we report its solution characteristics in respective columns.

6.1. Chord problem

Let us consider the following problem:

$$\min \frac{1}{2} \int_0^1 \|u'(t)\|^2 dt - \int_0^1 u(t) \top f(t) dt \quad \text{s.t. } u = (u_1, u_2) \top \in \mathcal{K},$$

where $\mathcal{K} = \{u \in (H^1_0(0, 1))^2 : u_2(t) \geq 0 \text{ on } (0, 0.5), \|u(t)\| \leq 1.4 \text{ on } (0.5, 1)\}$ and $f(t) = (36\pi^2 \sin 6\pi t, -4\pi^2 \sin 2\pi t) \top$. It describes the loaded chord fixed at the endpoints that is partially above the plan, partially inside the cylindrical tube; see Figure 1. The finite element approximation based on the continuous piecewise linear functions over a regular grid with $n = 4m$ degrees of freedom leads to
the constrained minimization problem that, contrary to (1), contains the fourth
unconstrained component \( x_4 \in \mathbb{R}^m \). Obviously, ALGORITHM PF may be easily
adapted for this new problem so that Theorem 4.3 remains valid.

Tables 1 and 2 show how ALGORITHM PF behaves for the inner solvers based
on \( J_{SC} \) and \( J_{AM} \), respectively. One can see that \( J_{AM} \) leads usually to a higher
performance of the algorithm in terms of \( n_A \). However, the progress measured by
the computational time is not so big, since the actions of \( P_{AM}^{-1} \) are costlier than of
\( P_{SC}^{-1} \). In order to obtain the same final precision of the solutions computed from
ALGORITHM PF and KPRGP, we adopt in ALGORITHM PF the stopping criterion
from KPRGP (instead of (11)), i.e., the iterations are stopped, when the relative
norm of the reduced gradient \([10, 21]\) for the projection of \( x^{(k)} \) on \( \Omega \) is less or
equal to \( 10^{-4} \). The efficiency of ALGORITHM PF exceeds KPRGP, if \( n \) is large.
The automatic choice \( r_{tol} = \kappa(A)^{-1/2} \) used in the first columns of the tables is
motivated by practical experience. When we replace the adaptive inner precision
control (45) by the non-adaptive one \( \epsilon_{kgn} = r_{tol} \times \epsilon \), then ALGORITHM PF generates
the same number of outer iterations \( \text{iter} \) for \( J_{SC} \) and \( J_{AM} \) (with the same \( r_{tol} \)).

The iteration history of the centering parameter \( \sigma_k \) and the steplength \( \alpha_k \) are
depicted in Figures 2 and 3 for \( n = 1024 \). One can see alternations of modestly
and strongly centered iterations so that the longer steps are generated after the
stronger centering. Figures 4 and 5 show the preconditioning effect. Although the
condition numbers \( \kappa(J_{SC}) \) and \( \kappa(J_{AM}) \) increase without any stint, the condition
numbers of the preconditioned matrices \( \kappa(P_{SC}^{-1}J_{SC}) \) and \( \kappa(P_{AM}^{-1}J_{AM}) \) are bounded
by the value \( \kappa(A) \approx 1.07 \times 10^5 \), as it is predicted by Corollary 5.4 (since \( \kappa(D) = 1 \)).

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Table 2. Chord problem, inner solver based on $J_{AM}$.

<table>
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<tr>
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<th>$PF(0.01, 0.9)$</th>
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</table>

Figure 2. Chord problem, $σ_k$ and $α_k$ for $J_{SC}$.

Figure 3. Chord problem, $σ_k$ and $α_k$ for $J_{AM}$.

6.2. Tresca friction

Let us consider a steel brick $S$ in $\mathbb{R}^3$ lying on a rigid obstacle. The brick occupies the domain $S = (0, 3) \times (0, 1) \times (0, 1)$ whose boundary $\partial S$ split into three parts $Γ_u = \{0\} \times (0, 1) \times (0, 1)$, $Γ_c = (0, 3) \times (0, 1) \times \{0\}$, and $Γ_p = \partial S \setminus (Γ_u \cup Γ_c)$ with different boundary conditions; see Figure 6. The zero displacements are prescribed on $Γ_u$ while the surface tractions act on $Γ_p$. On $Γ_c$ we consider the contact conditions, i.e., the non-penetration and the effect of Tresca friction. The elastic behavior of the brick is described by the Lamé equations that lead after finite element approximation to the symmetric, positive definite stiffness matrix $K \in \mathbb{R}^{3n \times 3n}$ and to a load vector $f \in \mathbb{R}^{3n}$, where $n$ is the number of finite element nodes in $S \setminus Γ_u$. By $m$ we denote the number of contact nodes, i.e., the nodes lying on $Γ_c \setminus Γ_u$. To describe the contact conditions, we introduce the full-rank matrices $N, T_1, T_2 \in \mathbb{R}^{m \times 3n}$ projecting displacements in the contact nodes to the normal and tangential directions, respectively. Finally, $d \in \mathbb{R}^m$ and $g \in \mathbb{R}^m$ collect distances to the obstacle and $a$-priori given slip bound values at the contact nodes, respectively.
The discrete contact problem with Tresca friction consists in seeking 
\((u^*, \lambda_{\nu}^*, \lambda_{\tau_1}^*, \lambda_{\tau_2}^*) \in \mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R}^m \times \mathbb{R}^m\) satisfying the following conditions [17]:

\[
K u - f + N^\top \lambda_{\nu} + T_1^\top \lambda_{\tau_1} + T_2^\top \lambda_{\tau_2} = 0, \\
N u - d \leq 0, \quad \lambda_{\nu} \geq 0, \quad \lambda_{\nu}^\top (N u - d) = 0, \\
\|\lambda_{\tau,i}\| \leq g_i, \\
\|\lambda_{\tau,i}\| < g_i \Rightarrow u_{\tau,i} = 0, \\
\|\lambda_{\tau,i}\| = g_i \Rightarrow \exists c_i \geq 0 : u_{\tau,i} = c_i \lambda_{\tau,i},
\]

where \(\lambda_{\tau,i} = (\lambda_{\tau_1,i}, \lambda_{\tau_2,i})^\top \in \mathbb{R}^2\), \(u_{\tau,i} = ((T_1 u)_i, (T_2 u)_i)^\top \in \mathbb{R}^2\), and \(g_i\) are the
entries of \( g \). Let us denote

\[
\lambda = \left( \lambda_\nu^T, \lambda_\tau_1^T, \lambda_\tau_2^T \right)^T, \quad B = \left( N^T, T_1^T, T_2^T \right)^T, \quad h = \left( d^T, 0^T, 0^T \right)^T.
\]

Since (48) gives \( u = K^{-1}(f - B^T\lambda) \), we can eliminate \( u \) from (48)-(50) that results in problem (1) for \( x = \lambda \) with

\[
A = BK^{-1}B^T, \quad b = BK^{-1}f - h, \quad l_i = 0, \quad i \in M_1.
\]

Recall that the preconditioners in ALGORITHM PF require the knowledge of the diagonal of \( A \). As its assemblage is now expensive, we use the following approximation:

\[
diag(A) \approx diag(B diag(K)^{-1}B^T).
\]

In Tables 3, 4 and in Figures 7, 8, 9, 10 for \( n = 18252 \), we present analogous tests as for the chord problem. We use in ALGORITHM PF the stopping criterion (11) with \( \epsilon = 10^{-2} \). The comparability of results computed by ALGORITHM PF and KPRGP is checked by the accuracy in satisfying (48), (49), and (50). Note that our choice of \( \epsilon \) is adequate to the precision control \( 10^{-4} \) in the stopping criterion of KPRGP that is sufficient for many engineering problems. One can see that only few strongly centered iterations are generated. The comparisons with KPRGP show higher efficiency of ALGORITHM PF. In the agreement with Corollary 5.4, the condition numbers of the preconditioned matrices are bounded by \( \kappa(A) \kappa(D) \), where \( \kappa(A) \approx 6.7 \times 10^3 \) and \( \kappa(D) \approx 4 \).

Table 3. Tresca friction, inner solver based on \( J_{SC} \).

<table>
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<tr>
<th>( n/m )</th>
<th>( \text{iter/n}_A )</th>
<th>( \text{time} )</th>
<th>( \text{iter/n}_A )</th>
<th>( \text{time} )</th>
<th>( \text{iter/n}_A )</th>
<th>( \text{time} )</th>
<th>( \text{iter/n}_A )</th>
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<td>14/92</td>
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<td>0.36</td>
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<td>0.48</td>
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</table>

Table 4. Tresca friction, inner solver based on \( J_{AM} \).

<table>
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<th>( n/m )</th>
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<th>( \text{time} )</th>
<th>( \text{iter/n}_A )</th>
<th>( \text{time} )</th>
<th>( \text{iter/n}_A )</th>
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An interior-point algorithm for 3D contact problems with friction

Figure 7. Tresca friction, $\sigma_k$ and $\alpha_k$ for $J_{SC}$.

Figure 8. Tresca friction, $\sigma_k$ and $\alpha_k$ for $J_{AM}$.

Figure 9. Tresca friction, the preconditioning effect for $J_{SC}$.

Figure 10. Tresca friction, the preconditioning effect for $J_{AM}$. 
6.3. Coulomb friction

Let us replace (50) by:

\[
\begin{align*}
\|\lambda_{r,i}\| & \leq F\lambda_{i,i}, \\
\|\lambda_{r,i}\| & < F\lambda_{i,i} \Rightarrow u_{r,i} = 0, \\
\|\lambda_{r,i}\| & = F\lambda_{i,i} \Rightarrow \exists c_i \geq 0 : u_{r,i} = c_i\lambda_{r,i},
\end{align*}
\]

\[i \in \mathcal{M}_1, \tag{51}\]

where \(F \in \mathbb{R}_+\) is the coefficient of Coulomb friction. The discrete contact problem with Coulomb friction consists in seeking \((u^*, \lambda^*_u, \lambda^*_r, \lambda^*_c) \in \mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R}^m \times \mathbb{R}^m\) satisfying (48), (49), and (51). Although there is no (evident) equivalency with any minimization problem, we will solve this problem by a simple modification of Algorithm PF.

Let us define the mapping \(\Psi : \mathbb{R}^m_+ \mapsto \mathbb{R}^m_+\), \(\Psi(g) = F\lambda_u, g \in \mathbb{R}^m_+\), where \(\lambda_u = \lambda_u(g)\) is the second component of the solution to the contact problem with Tresca friction. It is easily seen that a fixed point of \(\Psi\), i.e., the point \(g^* \in \mathbb{R}^m_+\) satisfying \(\Psi(g^*) = g^*\), determines a solution to the contact problem with Coulomb friction. The natural way how to compute fixed points is the method of successive approximations:

\[
\text{Initialize: } g^{(0)}, \quad g^{(p)} = \Psi(g^{(p-1)}), \quad p = 1, 2, \ldots. \tag{52}
\]

These iterations converge when \(\Psi\) is contractive that is guaranteed by sufficiently small \(F\) [14]. Note that each evaluation of the mapping \(\Psi\) in (52) requires to solve the contact problem with Tresca friction for that Algorithm PF may be used. In order to achieve high computational efficiency, we prefer an inexact implementation of (52), in which one iteration of Algorithm PF is performed in each successive approximation. As the first \(m\) components of \(x^{(k)}\) approximates \(\lambda_u\), we can equivalently perform this idea by modifying Algorithm PF so that \(g\) is updated in the beginning of each iteration, i.e., in step (1°), by

\[g := g^{(k)} = F((x_1^{(k)})^+, \ldots, (x_m^{(k)})^+)^\top,\]

where \(y^+ = \max\{0, y\}\) is the non-negative part of \(y \in \mathbb{R}\). Since the component \(z^{(k)}_i\) of \(v^{(k)}\) depends also on \(g\), we modify appropriately its value \((z^{(k)}_{i+m} := z^{(k)}_i - g^{(k-1)}_i + g^{(k)}_i, 1 \leq i \leq m, k > 0)\). We refer to this algorithm as Algorithm PFC. The convergence analysis of Section 4 is not valid, but it is obvious that, if the modified algorithm converges, then the limit point is a solution to the contact problem with Coulomb friction [1].

We compare the efficiency of Algorithm PFC with the method of successive approximations (52), in which KPRGP is used for solving inner problems with Tresca friction. We refer to this algorithm as KPRGPC. As KPRGP in KPRGPC is the inner iterative method, we apply the adaptive inner precision control analogous to this one described in Section 5.1. Based on our experiences with algorithms of this type [16, 23], we chose optimal values of the parameters defining the inner precision control so that also solution characteristics introduced below for KPRGPC are near to optimal. The value \(\text{iter}\) for KPRGPC denotes the number of successive iterations. In Algorithm PFC we use \(\epsilon = 10^{-4}\). The comparability of results computed by Algorithm PFC and KPRGPC is checked by the accuracy in satisfying (48), (49), and (51).

In Tables 5, 6, 7, and 8, we test Algorithm PFC for different coefficients of friction \(F = 0.1\) and 0.4. Note that Algorithm PFC behaves reasonably in all.
cases. One can see that the computations based on $J_{SC}$ are more efficient than these ones based on $J_{AM}$. Moreover, the comparison with KPRGPC shows better performance of Algorithm PFC in the most cases.

Table 5. Coulomb friction, $F = 0.1$, inner solver based on $J_{SC}$, $\delta = 0.9$.

<table>
<thead>
<tr>
<th>$n/m$</th>
<th>PFC(0.3, 0.99)</th>
<th>PFC(0.1, 0.99)</th>
<th>PFC(0.01, 0.99)</th>
<th>KPRGPC</th>
</tr>
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<td>31/214</td>
<td>0.66</td>
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<td>29/223</td>
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<td>42/456</td>
<td>28.47</td>
</tr>
<tr>
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<td>38/290</td>
<td>55.75</td>
<td>37/346</td>
<td>63.66</td>
</tr>
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<td>588.61</td>
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</table>

Table 6. Coulomb friction, $F = 0.1$, inner solver based on $J_{AM}$, $\delta = 0.9$.

<table>
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<tr>
<th>$n/m$</th>
<th>PFC(0.3, 0.99)</th>
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<th>PFC(0.01, 0.99)</th>
<th>KPRGPC</th>
</tr>
</thead>
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</tr>
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Table 7. Coulomb friction, $F = 0.4$, inner solver based on $J_{SC}$, $\delta = 0.9$.

<table>
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<tr>
<th>$n/m$</th>
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<th>PFC(0.1, 0.99)</th>
<th>PFC(0.01, 0.99)</th>
<th>KPRGPC</th>
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Table 8. Coulomb friction, $F = 0.4$, inner solver based on $J_{AM}$, $\delta = 0.9$.

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<td>35/354</td>
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</tr>
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</table>

7. Conclusions and comments

We have presented the new interior-point algorithm for the minimization of strictly quadratic functions subject to the simple bounds and separable quadratic inequality constraints. In the theoretical part of the paper, we proved that the algorithm
converges to the solution, when it generates a bounded sequence of iterations. Another theoretical result consists in the spectral analysis of the preconditioned matrices of the inner linear systems. It is shown that the eigenvalues lay in the positive interval whose bounds are determined solely by the matrix \( A \). We arrived at the result, in a sense optimal, that the condition numbers of the preconditioned matrices are uniformly bounded independently of the current interior-point iteration.

The second part of the paper is devoted to numerical tests. First, we found experimentally optimal values of the parameters determined the high computational performance of the algorithm for solving large scale problems. Then, we compared the efficiency with the active set algorithm proposed by the first author [10, 20, 21] in solving 3D contact problems of linear elasticity with friction. The efficiency of the interior-point algorithm is higher in almost all numerical experiments. Its lack consists in weaker theoretical results that do not comprise the prove of the convergence rate. Nevertheless, it seems that the algorithm is the promising tool for solving realistic problems of the real world.

The final comment is the qualitative comparison with other methods for solving contact problems of linear elasticity. One can divide them on the primal approaches, e.g., the non-smooth multiscale method of Krause [19], the primal-dual approaches, e.g., the semi-smooth Newton method of Hueber et al. [18], and the dual approaches, e.g., the FETI (finite element tearing and interconnecting) based domain decomposition method of Dostál et al. [7, 22]. Such classification is rough, since each of this approaches depends strongly on the algorithm for solving inner problems. Our interior-point algorithm may be conceived as the inner solver for the dual approach. The preconditioners discussed in the paper are related to the algorithm structure so that they remove singularities inherently given by the realization of the interior-point idea. In other words, they are the inner preconditioners of the interior-point algorithm. The outer preconditioner for the dual approach is the usage of the FETI method itself. Based on our spectral analysis, we deduce that the inner preconditioners presented in the paper are well situated to profit also from the FETI method. This topic together with other techniques exploiting the PDE structure are postponed to future works.

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