Trust-Region Interior-Point Method for Large Sparse l1 Optimization
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Abstract:

In this report, we propose an interior-point method for large sparse $l_1$ optimization. After a short introduction, the complete algorithm is introduced and some implementation details are given. We prove that this algorithm is globally convergent under standard mild assumptions. Thus relatively difficult $l_1$ optimization problems can be solved successfully. The results of computational experiments given in this report confirm efficiency and robustness of the proposed method.

Keywords:
Unconstrained optimization, large-scale optimization, nonsmooth optimization, minimax optimization, interior-point methods, modified Newton methods, computational experiments.

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1 Introduction

Consider the $l_1$ optimization problem: Minimize the function

$$F(x) = \sum_{i=1}^{m} |f_i(x)|,$$

where $f_i : \mathbb{R}^n \to \mathbb{R}$, $0 \leq i \leq m$, are smooth functions depending on $n_i$ variables and satisfying either Assumption 1 or Assumption 2. We assume that the function $F(x)$ is partially separable, which means that $n, m = \mathcal{O}(n)$ are large and $n_i = \mathcal{O}(1)$, $0 \leq i \leq m$, are small.

**Assumption 1.** Functions $f_i(x)$, $1 \leq i \leq m$, are twice continuously differentiable on $\text{conv} \mathcal{L}(F)$ for a sufficiently large upper bound $\overline{F}$, where $\mathcal{L}(F) = \{x \in \mathbb{R}^n : F(x) \leq \overline{F}\}$, and they have bounded first and second-order derivatives on $\text{conv} \mathcal{L}(F)$. Thus constants $\underline{g}$ and $\overline{G}$ exist such that $\|\nabla f_i(x)\| \leq \underline{g}$ and $\|\nabla^2 f_i(x)\| \leq \overline{G}$ for all $1 \leq i \leq m$ and $x \in \text{conv} \mathcal{L}(F)$.

**Assumption 2.** Functions $f_i(x)$, $1 \leq i \leq m$, are twice continuously differentiable on a sufficiently large convex compact set $\mathcal{D}$.

Since continuous functions attain their maxima on a compact set, Assumption 2 guarantees that constants $\overline{F}$, $\underline{g}$ and $\overline{G}$ exist such that $f_i(x) \leq \overline{F}$, $\|\nabla f_i(x)\| \leq \underline{g}$ and $\|\nabla^2 f_i(x)\| \leq \overline{G}$ for all $1 \leq i \leq m$ and $x \in \mathcal{D}$. The choice of $\mathcal{L}(F)$ and $\mathcal{D}$ will be discussed later (see Assumption 3). Note that the set $\mathcal{L}(F)$ used in Assumption 1 need not be compact.

The minimization of $F$ is equivalent to the sparse nonlinear programming problem with $n + m$ variables $x \in \mathbb{R}^n$, $z \in \mathbb{R}^m$:

$$\text{minimize } \sum_{i=1}^{m} z_i \text{ subject to } -z_i \leq f_i(x) \leq z_i, \quad 1 \leq i \leq m. \quad (2)$$

This problem satisfies the Mangasarian-Fromowitz constraint qualification conditions and the necessary first-order (KKT) conditions have the form

$$\sum_{i=1}^{m} u_i \nabla f_i(x) = 0, \quad z_i = |f_i(x)|, \quad |u_i| \leq 1 \quad \text{and} \quad u_i = \frac{f_i(x)}{|f_i(x)|} \quad \text{if} \quad |f_i(x)| > 0. \quad (3)$$

Problem (2) can be solved by an arbitrary nonlinear programming method utilizing sparsity (sequential linear programming [8], sequential quadratic programming [10], interior-point [1], [12], [25] and nonsmooth equation [13]). The original problem (1) is a special case of the polyhedral composite nonsmooth problem (see [7]) and it can be also solved by the trust-region methods described in [20] and [26].

In this report, we introduce a trust-region interior-point method that utilizes a special structure of the $l_1$ optimization problem. The constrained problem (2) is replaced.
by a sequence of unconstrained problems

\[
\text{minimize } B(x, z; \mu) = \sum_{i=1}^{m} z_i - \mu \sum_{i=1}^{m} \log(z_i - f_i(x)) - \mu \sum_{i=1}^{m} \log(z_i + f_i(x)) \\
= \sum_{i=1}^{m} z_i - \mu \sum_{i=1}^{m} \log(z_i^2 - f_i^2(x)) \quad (4)
\]

with a barrier parameter \(0 < \mu \leq \bar{\mu}\), where we assume that \(z_i > |f_i(x)|, 1 \leq i \leq m\), and \(\mu \to 0\) monotonically. Here \(B(x, z; \mu) : R^{n+m} \to R\) is a function of \(n + m\) variables \(x \in R^n, z \in R^m\).

The interior-point method described in this report is iterative, i.e., it generates a sequence of points \(x_k \in R^n, k \in N\) (\(N\) is a set of integers). For proving the global convergence, we need the following assumption concerning the function \(F(x)\) and the sequence \(\{x_k\}_1^\infty\).

**Assumption 3.** Either Assumption 1 holds and \(\{x_k\}_1^\infty \in \mathcal{L}(F)\) or Assumption 2 holds and \(\{x_k\}_1^\infty \in D\).

The interior-point method investigated in this report is a trust-region modification of the Newton method. Approximation of the Hessian matrix is computed by gradient differences which can be carried out efficiently if the Hessian matrix is sparse (see [3]). Since the Hessian matrix need not be positive definite in a non-convex case, a standard line-search realization cannot be used. There are two basic possibilities, either a trust-region approach or a line-search strategy with suitable restarts, which eliminate this insufficiency. We have implemented and tested both these possibilities and our tests have shown that the first possibility, used in Algorithm 1, is more efficient.

The report is organized as follows. In Section 2, we introduce the interior-point method for large sparse \(l_1\) optimization and describe a corresponding algorithm. Section 3 contains more details concerning this algorithm such as a trust-region strategy and a barrier parameter update. In Section 4 we study theoretical properties of the interior-point method and prove that this method is globally convergent if Assumption 3 holds. Finally, in Section 5 we present results of computational experiments confirming the efficiency of the proposed method.

## 2 Description of the method

Differentiating \(B(x, z; \mu)\) given by (4), we obtain necessary conditions for a minimum in the form

\[
\sum_{i=1}^{m} \frac{2\mu f_i(x)}{z_i^2 - f_i^2(x)} \nabla f_i(x) \overset{\Delta}{=} \sum_{i=1}^{m} u_i(x, z_i; \mu) \nabla f_i(x) = 0 \quad (5)
\]

and

\[
1 - \frac{2\mu z_i}{z_i^2 - f_i^2(x)} = 1 - u_i(x, z_i; \mu) \frac{z_i}{f_i(x)} = 0, \quad 1 \leq i \leq m. \quad (6)
\]
Denoting \( g_i(x) = \nabla f_i(x) \), \( 1 \leq i \leq m \), \( A(x) = [g_1(x), \ldots, g_m(x)] \),

\[
f(x) = \begin{bmatrix} f_1(x) \\ \vdots \\ f_m(x) \end{bmatrix}, \quad z = \begin{bmatrix} z_1 \\ \vdots \\ z_m \end{bmatrix}, \quad u(x, z; \mu) = \begin{bmatrix} u_1(x, z_1; \mu) \\ \vdots \\ u_m(x, z_m; \mu) \end{bmatrix}
\] (7)

and \( Z = \text{diag}(z_1, \ldots, z_m) \), we can write (5)–(6) in the form

\[
A(x)u(x, z; \mu) = 0, \quad u(x, z; \mu) = Z^{-1}f(x).
\] (8)

The system of \( n + m \) nonlinear equations (8) can be solved by the Newton method, which uses second-order derivatives. In every step of the Newton method, we solve a set of \( n + m \) linear equations to obtain increments \( \Delta x \) and \( \Delta z \) of \( x \) and \( z \), respectively. These increments can be used for obtaining new quantities

\[
x^+ = x + \alpha \Delta x, \quad z^+ = z + \alpha \Delta z,
\]

where \( \alpha > 0 \) is a suitable step-size. This is a standard way for solving general nonlinear programming problems. For the special nonlinear programming problem (2), the structure of \( B(x, z; \mu) \) allows us to obtain a minimizer \( z(x; \mu) \in R \) of the function \( B(x, z; \mu) \) for a given \( x \in R^n \).

**Lemma 1.** The function \( B(x, z; \mu) \) (with \( x \) fixed) has a unique stationary point, which is its global minimizer. This stationary point is characterized by the equations

\[
\frac{2\mu z_i(x; \mu)}{z_i^2(x; \mu) - f_i^2(x)} = 1 \quad \text{or} \quad z_i^2(x; \mu) - f_i^2(x) = 2\mu z_i(x; \mu), \quad 1 \leq i \leq m,
\] (9)

which have the solutions

\[
z_i(x; \mu) = \mu + \sqrt{\mu^2 + f_i^2(x)}, \quad 1 \leq i \leq m.
\] (10)

**Proof.** The function \( B(x, z; \mu) \) (with \( x \) fixed) is convex for \( z_i > |f_i(x)| \), \( 1 \leq i \leq m \), since it is a sum of convex functions. Thus if a stationary point of \( B(x, z; \mu) \) exists, it is its unique global minimizer. Differentiating \( B(x, z; \mu) \) by \( z \) (see (6)), we obtain the quadratic equations (9), which define its unique stationary point. \( \square \)

Assuming \( z = z(x; \mu) \) and using (6) and (10), we denote

\[
u_i(x; \mu) = u_i(x, z(x; \mu); \mu) = \frac{f_i(x)}{z_i(x; \mu)} = \frac{f_i(x)}{\mu + \sqrt{\mu^2 + f_i^2(x)}}, \quad 1 \leq i \leq m,
\] (11)

and

\[
B(x; \mu) = B(x, z(x; \mu); \mu) = \sum_{i=1}^{m} z_i(x; \mu) - \mu \sum_{i=1}^{m} \log(z_i^2(x; \mu) - f_i^2(x)) = \sum_{i=1}^{m} [z_i(x; \mu) - \mu \log(z_i(x; \mu))] - \mu m \log(2\mu).
\] (12)

In this case, the barrier function \( B(x; \mu) \) depends only on \( x \). In order to obtain a minimizer \( (x, z) \in R^{n+m} \) of \( B(x, z; \mu) \), it suffices to minimize \( B(x; \mu) \) over \( R^n \).
Lemma 2. Consider the barrier function (12). Then
\[ \nabla B(x; \mu) = A(x)u(x; \mu) \]  
(13)
and
\[ \nabla^2 B(x; \mu) = G(x; \mu) + A(x)V(x; \mu)A^T(x), \]  
(14)
where
\[ G(x; \mu) = \sum_{i=1}^{m} u_i(x; \mu)G_i(x) \]  
(15)
with \( G_i(x) = \nabla^2 f_i(x), \) \( 1 \leq i \leq m, \) and \( V(x; \mu) = \text{diag}(v_1(x; \mu), \ldots, v_m(x; \mu)) \) with
\[ v_i(x; \mu) = \frac{2\mu}{z_i^2(x; \mu) + f_i^2(x)}, \quad 1 \leq i \leq m. \]  
(16)

Proof. Differentiating (12), we obtain
\[ \nabla B(x; \mu) = \sum_{i=1}^{m} \nabla z_i(x; \mu) - 2\mu \sum_{i=1}^{m} \frac{z_i(x; \mu)\nabla z_i(x; \mu) - f_i(x)g_i(x)}{z_i^2(x; \mu) - f_i^2(x)} \] 
\[ = \sum_{i=1}^{m} \left( 1 - \frac{2\mu z_i(x; \mu)}{z_i^2(x; \mu) - f_i^2(x)} \right) \nabla z_i(x; \mu) + \sum_{i=1}^{m} \frac{2\mu f_i(x)g_i(x)}{z_i^2(x; \mu) - f_i^2(x)} \] 
\[ = \sum_{i=1}^{m} u_i(x; \mu)g_i(x) = A(x)u(x; \mu) \]
by (9) and (5). Differentiating (9), one has
\[ \frac{\nabla z_i(x; \mu)}{z_i^2(x; \mu) - f_i^2(x)} - \frac{2z_i(x; \mu)(z_i(x; \mu)\nabla z_i(x; \mu) - f_i(x)g_i(x))}{(z_i^2(x; \mu) - f_i^2(x))^2} = 0 \]
for \( 1 \leq i \leq m, \) which gives
\[ \nabla z_i(x; \mu) = \frac{2z_i(x; \mu)f_i(x)g_i(x)}{z_i^2(x; \mu) + f_i^2(x)} \]  
(17)
for \( 1 \leq i \leq m \) after arrangements. Thus
\[ \nabla u_i(x; \mu) = \nabla \left( \frac{f_i(x)}{z_i(x; \mu)} \right) = \frac{z_i(x; \mu)g_i(x) - f_i(x)\nabla z_i(x; \mu)}{z_i^2(x; \mu)} \] 
\[ = \left( 1 - \frac{2f_i^2(x)}{z_i^2(x; \mu) + f_i^2(x)} \right) \frac{g_i(x)}{z_i(x; \mu)} \] 
\[ = \frac{z_i^2(x; \mu) - f_i^2(x)}{z_i^2(x; \mu) + f_i^2(x)} \frac{g_i(x)}{z_i(x; \mu)} \] 
\[ = \frac{2\mu}{z_i^2(x; \mu) + f_i^2(x)} g_i(x) = v_i(x; \mu)g_i(x) \]
by (11), (17), (9) and (16). Differentiating (13) and using the previous expression, we obtain
\[\nabla^2 B(x; \mu) = \nabla \sum_{i=1}^{m} u_i(x; \mu) g_i(x) \]
\[= \sum_{i=1}^{m} u_i(x; \mu) G_i(x) + \sum_{i=1}^{m} \nabla u_i(x; \mu) g_i^T(x) \]
\[= \sum_{i=1}^{m} u_i(x; \mu) G_i(x) + \sum_{i=1}^{m} v_i(x; \mu) g_i(x) g_i^T(x),\]
which is equation (14).

**Lemma 3.** Let a vector \(d \in \mathbb{R}^n\) solve the equation
\[\nabla^2 B(x; \mu)d = -g(x; \mu),\] (18)
where \(g(x; \mu) = \nabla B(x; \mu) \neq 0\). If the matrix \(G(x; \mu)\) is positive definite, then \(d^T g(x; \mu) < 0\) (the direction vector \(d\) is descent for \(B(x; \mu)\)).

**Proof.** Equation (18) implies
\[d^T g(x; \mu) = -d^T \nabla^2 B(x; \mu)d = -d^T G(x; \mu)d - d^T A(x) V(x; \mu) A^T(x)d \leq -d^T G(x; \mu)d,\]
since \(V(x; \mu)\) is positive definite by (16). Thus \(d^T g(x; \mu) < 0\) if \(G(x; \mu)\) is positive definite. \(\square\)

Expression (16) implies that \(v_i(x; \mu)\) is bounded if \(f_i^2(x)\) is bounded from zero. If \(f_i^2(x)\) tends to zero faster than \(\mu\) then \(v_i(x; \mu)\) can tend to infinity and \(\nabla^2 B(x; \mu)\) can be ill-conditioned (see (14)). The following lemma gives the upper bound for \(\|\nabla^2 B(x; \mu)\|\).

**Lemma 4.** If Assumption 3 holds, then
\[\|\nabla^2 B(x; \mu)\| \leq m(\overline{G} + \overline{g}^2\|V(x; \mu)\|) \leq \frac{\overline{C}}{\mu},\]
where \(\overline{C} = m(2\mu \overline{G} + \overline{g}^2)/2\).

**Proof.** Using (14) and Assumption 3, we obtain
\[\|\nabla^2 B(x; \mu)\| = \|G(x; \mu) + A(x) V(x; \mu) A^T(x)\| \]
\[\leq \left\| \sum_{i=1}^{m} u_i(x; \mu) G_i(x) \right\| + \left\| \sum_{i=1}^{m} v_i(x; \mu) g_i(x) g_i^T(x) \right\| \]
\[\leq m \overline{G} + m \overline{g}^2\|V(x; \mu)\|,\]

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where $\rho < \beta \leq 1$, is equivalent $\beta \ll 1$, where $\Delta$ is a trust region radius (more details are given in Section 3). The direction vector using either gradient differences or variable metric updates. In the first case, $G$ is an approximation of $G(x; \mu)$ obtained by using either gradient differences or variable metric updates. In the first case, $G$ is computed by differences $A(x + \delta v_j)u(x; \mu) - A(x)u(x; \mu)$ for a suitable set of vectors $v_j$, $j = 1, 2, \ldots, \mathbf{u}$, where $\mathbf{u} \ll n$. Determination of vectors $v_j, j = 1, 2, \ldots, \mathbf{u}$, is equivalent to a graph coloring problem (see [3]). The corresponding code is proposed in [2]. In the second case, $G$ is defined by the expression

$$G = \sum_{i=1}^{m} u_i(x; \mu) G_i,$$

since $|u_i(x; \mu)| \leq 1, 1 \leq i \leq m$, by (11). Since $V(x; \mu)$ is diagonal, one has

$$\|V(x; \mu)\| = \max_{1 \leq i \leq m} |v_i(x; \mu)| = \max_{1 \leq i \leq m} \left( \frac{2\mu}{z_i^2(x; \mu) + f_i^2(x)} \right)$$

(19)

by (16). Using (10), we can write

$$z_i^2(x; \mu) + f_i^2(x) = \left( \mu + \sqrt{\mu^2 + f_i^2(x)} \right)^2 + f_i^2(x)$$

$$= 2 \left( \mu^2 + \mu \sqrt{\mu^2 + f_i^2(x)} + f_i^2(x) \right) \geq 4\mu^2$$

for all $1 \leq i \leq m$, which together with (19) proves the lemma. \hfill \Box

The vector $d \in \mathbb{R}^n$ obtained by solving (18) is descent for $B(x; \mu)$ if the matrix $G(x; \mu)$ is positive definite. Unfortunately, the positive definiteness of this matrix is not assured, which causes that the standard line-search methods cannot be used. For this reason, the trust-region methods were developed. These methods use a direction vector obtained as an approximate minimizer of the quadratic subproblem

$$\text{minimize} \quad Q(d) = \frac{1}{2} d^T \nabla^2 B(x; \mu)d + g^T(x; \mu)d \quad \text{subject to} \quad \|d\| \leq \Delta,$$

(20)

where $\Delta$ is a trust region radius (more details are given in Section 3). The direction vector $d$ serves for obtaining a new point $x^+ \in \mathbb{R}^n$. Denoting

$$\rho(d) = \frac{B(x + d; \mu) - B(x; \mu)}{Q(d)},$$

(21)

we set

$$x^+ = x \quad \text{if} \quad \rho(d) < \underline{\rho} \quad \text{or} \quad x^+ = x + d \quad \text{if} \quad \rho(d) \geq \underline{\rho}$$

(22)

and update the trust region radius in such a way that

$$\underline{\rho}\|d\| \leq \Delta^+ \leq \underline{\beta}\|d\| \quad \text{if} \quad \rho(d) < \underline{\rho} \quad \text{or} \quad \Delta \leq \Delta^+ \leq \tau\Delta \quad \text{if} \quad \rho(d) \geq \underline{\rho},$$

(23)

where $0 < \underline{\rho} < \bar{\rho} < 1$ and $0 < \underline{\beta} \leq \bar{\beta} < 1 < \tau$.

In (20), we assume that $\nabla^2 B(x; \mu) = G + A(x)V(x; \mu)A^T(x)$, where $G = G(x; \mu)$ (see (14)). In practical computations, $G$ is an approximation of $G(x; \mu)$ obtained by using either gradient differences or variable metric updates. In the first case, $G$ is computed by differences $A(x + \delta v_j)u(x; \mu) - A(x)u(x; \mu)$ for a suitable set of vectors $v_j$, $j = 1, 2, \ldots, \mathbf{u}$, where $\mathbf{u} \ll n$. Determination of vectors $v_j, j = 1, 2, \ldots, \mathbf{u}$, is equivalent to a graph coloring problem (see [3]). The corresponding code is proposed in [2]. In the second case, $G$ is defined by the expression
where approximations $G_i$ of $\nabla^2 f_i(x)$ are computed by using variable metric updates described in [11]. In this case, we assume that problem (1) is "partially separable", which means that functions $f_i(x)$, $1 \leq i \leq m$, depend on a small number of variables ($n_i$, say, with $n_i = \mathcal{O}(1)$, $1 \leq i \leq m$). More details are given in the next section.

Now we are in a position to describe the basic algorithm.

**Algorithm 1.**

**Data:** The termination parameter $\varepsilon > 0$, the minimum value of the barrier parameter $\mu > 0$, the rate of the barrier parameter decrease $0 < \tau < 1$, the trust-region parameters $0 < \rho < \rho' < 1$, the trust-region coefficients $0 < \beta \leq \beta' < 1 < \gamma$, the step bound $\Delta > 0$.

**Input:** A sparsity pattern of the matrix $A$. An initial estimation of the vector $x$.

**Step 1:** *Initiation.* Choose the initial barrier parameter $\mu > 0$ and the initial trust-region radius $0 < \Delta \leq \Delta$. Determine a sparsity pattern of the matrix $\nabla^2 B$ from the sparsity pattern of the matrix $A$. Carry out a symbolic decomposition of $\nabla^2 B$. Compute the values $f_i(x)$, $1 \leq i \leq m$, and $F(x) = \sum_{1 \leq i \leq m} |f_i(x)|$. Set $k := 0$ (the iteration count).

**Step 2:** *Termination.* Determine the vector $z(x; \mu)$ by (10) and the vector $u(x; \mu)$ by (8). Compute the matrix $A(x)$ and the vector $g(x; \mu) = A(x)u(x; \mu)$. If $\mu \leq \underline{\mu}$ and $\|g(x; \mu)\| \leq \varepsilon$, then terminate the computation. Otherwise set $k := k + 1$.

**Step 3:** *Approximation of the Hessian matrix.* Compute approximation $G$ of Hessian matrix $G(x; \mu)$ by using either gradient differences or variable metric updates. Determine the Hessian matrix $\nabla^2 B(x; \mu)$ by (14).

**Step 4:** *Direction determination.* Determine the vector $d$ as an approximate solution of the trust-region subproblem (20).

**Step 5:** *Step-length selection.* Set $x := x^+$, where $x^+$ is a point defined by (22). Compute the values $f_i(x)$, $1 \leq i \leq m$, and $F(x) = \sum_{1 \leq i \leq m} |f_i(x)|$.

**Step 6:** *Trust-region update.* Determine a new trust-region radius $\Delta$ satisfying (23) and set $\Delta := \min(\Delta, \Delta)$.

**Step 7:** *Barrier parameter update.* If $\rho(d) \geq \underline{\rho}$ (where $\rho(d)$ is given by (21)), determine a new value of the barrier parameter $\mu \geq \underline{\mu}$ (not greater than the current one) by the procedure described in Section 3. Go to Step 2.

The use of the maximum step-length $\Delta$ has no theoretical significance but is very useful for practical computations. First, the problem functions can sometimes be evaluated only in a relatively small region (if they contain exponentials) so that the maximum step-length is necessary. Secondly, the problem can be very ill-conditioned far from the solution point, thus large steps are unsuitable. Finally, if the problem has more local solutions, a suitably chosen maximum step-length can cause a local solution
with a lower value of $F$ to be reached. Therefore, the maximum step-length $\Delta$ is a parameter, which is most frequently tuned.

An important part of Algorithm 1 is an update of the barrier parameter $\mu$. There are several influences that should be taken into account, which make the updating procedure rather complicated.

### 3 Implementation details

In Section 2, we have pointed out that the direction vector $d \in \mathbb{R}^n$ should be a solution of the quadratic subproblem (20). Usually, an inexact approximate solution suffices. There are several ways for computing suitable approximate solutions (see, e.g., [5], [14], [18], [19], [22], [23], [24]). We have used two approaches based on direct decompositions of the matrix $\nabla^2 B$ (to simplify the notation, we omit arguments $x$ and $\mu$ in the subsequent considerations, i.e., we will write $\nabla^2 B$ and $g$ instead of $\nabla^2 B(x; \mu)$ and $g(x; \mu)$).

The first strategy, the dog-leg method described in [5], [19], seeks $d$ as a linear combination of the Cauchy step $d_C = -\left(g^T g / g^T \nabla^2 B g\right) g$ and the Newton step $d_N = -\left(\nabla^2 B\right)^{-1} g$. The Newton step is computed by using either the sparse Gill-Murray decomposition [9] or the sparse Bunch-Parlett decomposition [6]. The sparse Gill-Murray decomposition has the form $\nabla^2 B + E = LDL^T = R^T R$, where $E$ is a positive semidefinite diagonal matrix (which is equal to zero when $\nabla^2 B$ is positive definite), $L$ is a lower triangular matrix, $D$ is a positive definite diagonal matrix and $R$ is an upper triangular matrix. The sparse Bunch-Parlett decomposition has the form $\nabla^2 B = PLML^T P^T$, where $P$ is a permutation matrix, $L$ is a lower triangular matrix and $M$ is a block-diagonal matrix with $1 \times 1$ or $2 \times 2$ blocks (which is indefinite when $\nabla^2 B$ is indefinite). The following algorithm is a typical implementation of the dog-leg method.

**Algorithm A:** Data $\Delta > 0$.

**Step 1:** If $g^T \nabla^2 B g \leq 0$, set $d := -\left(\Delta / \|g\|\right) g$ and terminate the computation.

**Step 2:** Compute the Cauchy step $d_C = -\left(g^T g / g^T \nabla^2 B g\right) g$. If $\|d_C\| \geq \Delta$, set $d := \left(\Delta / \|d_C\|\right) d_C$ and terminate the computation.

**Step 3:** Compute the Newton step $d_N = -\left(\nabla^2 B\right)^{-1} g$. If $(d_N - d_C)^T d_C \geq 0$ and $\|d_N\| \leq \Delta$, set $d := d_N$ and terminate the computation.

**Step 4:** If $(d_N - d_C)^T d_C \geq 0$ and $\|d_N\| > \Delta$, determine a number $\theta$ in such a way that $d_C^T d_C / d_N^T d_N \leq \theta \leq 1$, choose $\alpha > 0$ such that $\|d_C + \alpha(\theta d_N - d_C)\| = \Delta$, set $d := d_C + \alpha(\theta d_N - d_C)$ and terminate the computation.

**Step 5:** If $(d_N - d_C)^T d_C < 0$, choose $\alpha > 0$ such that $\|d_C + \alpha(d_C - d_N)\| = \Delta$, set $d := d_C + \alpha(d_C - d_N)$ and terminate the computation.

The second strategy, the optimum step method, computes a more accurate solution...
of (20) by using the Newton method applied to the nonlinear equation

\[
\frac{1}{\|d(\lambda)\|} - \frac{1}{\Delta} = 0,
\]

where \((\nabla^2 B + \lambda I)d(\lambda) = -g\). This way, described in [18] in more details, follows from the KKT conditions for (20). Since the Newton method applied to (24) can be unstable, the safeguards (lower and upper bounds to \(\lambda\)) are usually used. The following algorithm is a typical implementation of the optimum step method.

**Algorithm B:** Data 0 < \(\delta\) < 1 < \(\bar{\delta}\) (usually \(\delta = 0.9\) and \(\bar{\delta} = 1.1\)), \(\Delta > 0\).

**Step 1:** Determine \(\nu\) as the maximum diagonal element of the matrix \(-\nabla^2 B\). Compute \(\lambda = \|g\|/\Delta + \|\nabla^2 B\|\), \(\Delta = \|g\|/\Delta - \|\nabla^2 B\|\) and set \(\lambda := \max(0, \nu, \lambda)\), \(\lambda := \lambda\). Set \(l = 0\) (the inner iteration count).

**Step 2:** If \(l > 0\) and \(\lambda \leq \nu\), set \(\lambda := \sqrt{\lambda\lambda}\).

**Step 3:** Determine the Gill-Murray decomposition \(\nabla^2 B + \lambda I + E = R^T R\). If \(E = 0\) (i.e. if \(\nabla^2 B + \lambda I\) is positive definite), go to Step 4. In the opposite case, determine a vector \(v \in R^n\) such that \(\|v\| = 1\) and \(v^T(\nabla^2 B + \lambda I)v \leq 0\), set \(\nu := \nu - v^T(\nabla^2 B + \lambda I)v\), \(\lambda := \max(\nu, \lambda)\), \(l := l + 1\) and go to Step 2.

**Step 4:** Determine a vector \(d \in R^n\) as a solution of the equation \(R^T Rd + g = 0\). If \(\|d\| > \bar{\delta}\Delta\), set \(\lambda := \lambda\) and go to Step 6. If \(\delta\Delta \leq \|d\| \leq \bar{\delta}\Delta\), terminate the computation. If \(\|d\| < \delta\Delta\) and \(\lambda = 0\), terminate the computation. If \(\|d\| < \delta\Delta\) and \(\lambda \neq 0\), set \(\lambda := \lambda\) and go to Step 5.

**Step 5:** Determine a vector \(v \in R^n\) as a good approximation of the eigenvector corresponding to the minimum eigenvalue of \(\nabla^2 B\) in such a way that \(\|v\| = 1\) and \(v^T d \geq 0\) (this vector can be determined from the decomposition \(R^T R\) in the way used in subroutines of the LAPACK library). Determine a number \(\alpha \geq 0\) such that \(\|d + \alpha v\| = \Delta\). If \(\alpha^2\|Rv\|^2 \leq (1 - \bar{\delta}^2)(\|Rd\|^2 + \lambda\Delta^2)\), set \(d := d + \alpha v\) and terminate the computation. In the opposite case, set \(\nu := \nu - \|Rv\|^2\), \(\lambda := \max(\nu, \lambda)\) and go to Step 6.

**Step 6:** Determine a vector \(v \in R^n\) as a solution of the equation \(R^T v = d\) and set

\[
\lambda := \lambda + \|d\|^2 \left(\frac{\|d\| - \Delta}{\Delta}\right).
\]

If \(\lambda < \lambda\), set \(\lambda := \lambda\). If \(\lambda > \lambda\), set \(\lambda := \lambda\). Set \(l := l + 1\) and go to Step 2.

The above algorithms generate the direction vectors such that

\[
\|d\| \leq \bar{\delta}\Delta, \\
\|d\| < \delta\Delta \Rightarrow \nabla^2 Bd = -g, \\
-\nabla^2 B = -g \min\left(\|d\|, \frac{\|g\|}{\|\nabla^2 B\|}\right),
\]

where \(\mathbf{Q}(d)\) is a positive semi-definite matrix and \(\mathbf{Q}(d) = \mathbf{Q}(d)\) is a positive semi-definite matrix.
where $0 < \rho < 1$ is a constant depending on the particular algorithm. These inequalities and (23) imply (see [21]) that a constant $0 < \zeta < 1$ exists such that

$$\|d\| \geq \zeta \|\tilde{g}\| \frac{\mu}{C},$$

(25)

where $\|\tilde{g}\|$ is the minimum norm of all gradients that have been computed so far and $\bar{C}$ is a constant used in Lemma 4. Thus using (21), (22) and (25), one has

$$B(x + d; \mu) - B(x; \mu) \leq \rho Q(d) \leq -\bar{C} \mu \|\tilde{g}\|^2 \text{ if } \rho(d) \geq \rho,$$

where $\bar{C} = \rho \bar{g} \bar{g} / \bar{C}$.

The update of the trust region radius satisfying (23) requires a more detailed specification. In our implementation, we have set

$$
\begin{align*}
\Delta^+ &= \beta \|d\| \text{ if } \rho(d) < \bar{\rho}_1 \text{ and } \tilde{\Delta} < \beta \|d\|, \\
\Delta^+ &= \tilde{\Delta} \text{ if } \rho(d) < \bar{\rho}_1 \text{ and } \beta \|d\| \leq \tilde{\Delta} \leq \bar{\rho} \|d\|, \\
\Delta^+ &= \bar{\rho} \|d\| \text{ if } \rho(d) < \bar{\rho}_1 \text{ and } \bar{\rho} \|d\| \leq \tilde{\Delta}, \\
\Delta^+ &= \Delta \text{ if } \bar{\rho}_1 \leq \rho(d) \leq \bar{\rho}_2, \\
\Delta^+ &= \Delta \text{ if } \bar{\rho}_2 < \rho(d) \text{ and } \|d\| < \hat{\Delta} \Delta, \\
\Delta^+ &= \hat{\Delta} \Delta \text{ if } \bar{\rho}_2 < \rho(d) \text{ and } \|d\| \geq \hat{\Delta} \Delta,
\end{align*}
$$

where $0 < \rho < \bar{\rho} = \bar{\rho}_1 < \bar{\rho}_2 < 1$, $\hat{\Delta}$ is a value used in Algorithm B ($\hat{\Delta} = 1$ in Algorithm A) and $\tilde{\Delta}$ is a value obtained by the quadratic interpolation.

Matrix $G$ appearing in Step 3 of Algorithm 1 can be computed by using gradient differences as was mentioned in the previous section. Alternatively, safeguarded BFGS updates can be applied efficiently. In this case, $G^+ = \sum_{i=1}^m u_i(x^+; \mu^+)G^+_i$, where $x^+$ is the vector of variables in the next iteration and $G^+_i$, $1 \leq i \leq m$ are computed by the following way. Let $R^n_i \subset R^n$, $1 \leq i \leq m$, be subspaces defined by $n_i$ variables on which each $f_i$ depends and $Z_i \subset R^{n \times n_i}$ be the matrix whose columns form the canonical orthonormal basis in $R^n_i$ (i.e., they are columns of the unit matrix). Then we can define reduced approximations of the Hessian matrices $\tilde{G}_i = Z_i^T G_i Z_i$, $1 \leq i \leq m$. New reduced approximations of the Hessian matrices are computed by the formulas

$$
\begin{align*}
\tilde{G}^+_i &= \tilde{G}_i + \frac{\tilde{y}_i \tilde{y}^T_i}{\tilde{s}_i \tilde{y}_i} - \frac{\tilde{G}_i \tilde{s}_i \tilde{s}^T_i \tilde{G}_i}{\tilde{s}_i \tilde{G}_i \tilde{s}_i}, \quad \tilde{s}_i \tilde{y}_i > 0, \\
\tilde{G}^+_i &= \tilde{G}_i, \quad \tilde{s}_i \tilde{y}_i \leq 0,
\end{align*}
$$

where $\tilde{s}_i = Z_i^T (x^+ - x)$, $\tilde{y}_i = Z_i^T (\nabla f_i(x^+) - \nabla f_i(x))$, $1 \leq i \leq m$. Finally $G^+_i = Z_i \tilde{G}^+_i Z_i^T$, $1 \leq i \leq m$. In the first iteration we set $\hat{G}_i = I$, $1 \leq i \leq m$ ($I$ is the unit matrix).

A very important part of Algorithm 1 is the update of the barrier parameter $\mu$. There are two requirements, which play opposite roles. First $\mu \to 0$ should hold, since this is the main property of every interior point method. On the other hand, Lemma 4
implies that $\nabla^2 B(x; \mu)$ can be ill-conditioned if $\mu$ is too small. Thus the lower bound $\mu$ for $\mu$ is used in Algorithm 1 (we recommend value $10^{-8}$ in the double precision arithmetic).

Algorithm 1 is also sensitive on the way in which the barrier parameter decreases. We have tested various possibilities for the barrier parameter update including simple geometric sequences, which were proved to be unsuitable. Better results were obtained by setting
\[ \mu^+ = \max(\mu, \|g\|^2) \] if $\rho(d) \geq \rho$ and $\|g\|^2 \leq \tau \mu$ \hfill (27)
(where $0 < \tau < 1$) and $\mu^+ = \mu$ otherwise.

4 Global convergence

In the subsequent considerations, we will assume that $z = \mu = 0$ and all computations are exact. We will investigate the infinite sequence $\{x_k\}_1^\infty$ generated by Algorithm 1.

**Lemma 5.** Let Assumption 3 be satisfied. Then the values $\{\mu_k\}^\infty_1$, generated by Algorithm 1, form a non-increasing sequence such that $\mu_k \to 0$. Moreover, there is an infinite subset $K \subset N$ such that $\rho(d_k) \leq \rho$ and $\|g(x_k; \mu_k)\|^2 \leq \tau \mu_k$ for all $k \in K$.

**Proof.** (a) First, we prove that $B(x; \mu)$ is bounded from below if $\mu$ is fixed. Since $z_i(x; \mu) \geq 2\mu$ and
\[ \frac{\partial B(x; \mu)}{\partial z_i} = 1 - \frac{\mu}{z_i(x; \mu)} \geq 1 - \frac{\mu}{2\mu} = \frac{1}{2} \]
for $1 \leq i \leq m$ by (10) and (12), function $B(x; \mu)$ attains its minimum if $z_i(x; \mu) = 2\mu$ for $1 \leq i \leq m$. Thus
\[ B(x; \mu) = \sum_{i=1}^m [z_i(x; \mu) - \mu \log(z_i(x; \mu))] - m\mu \log(2\mu) \]
\[ \geq m[2\mu - \mu \log(2\mu)] - m\mu \log(2\mu) = 2m\mu(1 - \log(2\mu)). \hfill (28) \]

(b) Now we prove that the set $K$ of indices for which $\mu_k$ is updated is infinite. Note that $K$ is the set of indices such that $\rho(d_k) \leq \rho$ and $\|g(x_k; \mu_k)\|^2 \leq \tau \mu_k$ (see (27)). If $K$ was finite, an index $k \in N$ would exist such that $\mu_k = \mu_k \forall k \geq k$. Since the function $B(x; \mu_k)$ is continuous, uniformly bounded from below by (a), $\|\nabla^2 B(x; \mu_k)\|$ is uniformly bounded from above by Lemma 4 and (22) holds for all $k \geq k$, it can be proved (see [4]) that $\lim_{k \to \infty} \|g(x_k; \mu_k)\| = 0$. Thus an index $l \geq k$ exists such that $\rho(d_l) \geq \rho$ and $\|g(x_l; \mu_l)\|^2 \leq \tau \mu_l$ (since $\rho(d_k) < \rho$ implies that $x_k$ and, therefore, $\|g(x_k; \mu_k)\|$ does not change). Thus $\mu_{l+1} = \|g(x_l; \mu_l)\|^2 \leq \tau \mu_k \mu_k$ by (27), which is in a contradiction with the assumption that $\mu_k = \mu_k \forall k \geq k$. Since we have proved that the set $K$ of indices for which $\mu_k \leq \tau \mu_k$ is infinite, we can conclude that $\mu_k \to 0$. \hfill \Box

Now we will prove that
\[ B(x_{k+1}; \mu_{k+1}) \leq B(x_{k+1}; \mu_k) - L(\mu_{k+1} - \mu_k) \hfill (29) \]
for some constant $L \in R$. For this purpose, we consider that $z(x; \mu)$ and $B(x; \mu)$ are functions of $\mu$ and we write $z(x, \mu) = z(x; \mu)$ and $B(x, \mu) = B(x; \mu)$.

**Lemma 6.** Let $z_i(x, \mu)$, $1 \leq i \leq m$, be the values given by Lemma 1 (for fixed $x$ and variable $\mu$). Then
\[
\frac{\partial z_i(x, \mu)}{\partial \mu} > 1, \quad \forall 1 \leq i \leq m,
\]
and
\[
\frac{\partial B(x, \mu)}{\partial \mu} = -\sum_{i=1}^{m} \log(z_i^2(x, \mu) - f_i^2(x)) = -\sum_{i=1}^{m} \log(2\mu z_i(x, \mu)).
\]

**Proof.** Differentiating the expressions $z_i(x, \mu) = \mu + \sqrt{\mu^2 + f_i^2(x)}$, $1 \leq i \leq m$, following from Lemma 1, we obtain
\[
\frac{\partial z_i(x, \mu)}{\partial \mu} = 1 + \frac{\mu}{\sqrt{\mu^2 + f_i^2(x)}} > 1, \quad 1 \leq i \leq m.
\]
Differentiating the function
\[
B(x, \mu) = \sum_{i=1}^{m} z_i(x, \mu) - \mu \sum_{i=1}^{m} \log(z_i^2(x, \mu) - f_i^2(x)),
\]
one has
\[
\frac{\partial B(x, \mu)}{\partial \mu} = \sum_{i=1}^{m} \frac{\partial z_i(x, \mu)}{\partial \mu} - \sum_{i=1}^{m} \log(z_i^2(x, \mu) - f_i^2(x)) - \sum_{i=1}^{m} \frac{2\mu z_i(x, \mu)}{z_i^2(x, \mu) - f_i^2(x)} \frac{\partial z_i(x, \mu)}{\partial \mu}
\]
\[
= \sum_{i=1}^{m} \frac{\partial z_i(x, \mu)}{\partial \mu} \left(1 - \frac{2\mu z_i(x, \mu)}{z_i^2(x, \mu) - f_i^2(x)}\right) - \sum_{i=1}^{m} \log(z_i^2(x, \mu) - f_i^2(x))
\]
\[
= -\sum_{i=1}^{m} \log(z_i^2(x, \mu) - f_i^2(x)) = -\sum_{i=1}^{m} \log(2\mu z_i(x, \mu))
\]
by (9). \hfill \Box

**Lemma 7.** Let Assumption 3 be satisfied. Then (29) holds with some constant $L \in R$.

**Proof.** Using Lemma 6, the mean value theorem and (10), we can write
\[
B(x_{k+1}, \mu_{k+1}) - B(x_{k+1}, \mu_k) = -\sum_{i=1}^{m} \log(2\tilde{\mu}_k z_i(x_{k+1}, \tilde{\mu}_k)) (\mu_{k+1} - \mu_k)
\]
\[
\leq -\sum_{i=1}^{m} \log \left(2\tilde{\mu}_k (2\tilde{\mu}_k + \overline{F}) \right) (\mu_{k+1} - \mu_k)
\]
\[
\leq -\sum_{i=1}^{m} \log \left(2\overline{\mu}_k (2\overline{\mu}_k + \overline{F}) \right) (\mu_{k+1} - \mu_k)
\]
\[
\Delta = -L(\mu_{k+1} - \mu_k),
\]
where $0 < \mu_{k+1} \leq \tilde{\mu}_k \leq \mu_k \leq \overline{\mu}$. \hfill \Box
**Theorem 1.** Let Assumption 3 be satisfied. Consider the sequence \( \{x_k\}^\infty_{k=1} \), generated by Algorithm 1. Then

\[
\liminf_{k \to \infty} \sum_{i=1}^m u_i(x_k; \mu_k)g_i(x_k) = 0,
\]

and

\[
\lim_{k \to \infty} (z_i^2(x_k; \mu_k) - f_i^2(x_k)) = 0, \quad |u_i(x_k; \mu_k)| \leq 1,
\]

\[
\lim_{k \to \infty} u_i(x_k; \mu_k) = 1 \text{ if } \liminf_{k \to \infty} f_i(x_k) > 0,
\]

\[
\lim_{k \to \infty} u_i(x_k; \mu_k) = -1 \text{ if } \limsup_{k \to \infty} f_i(x_k) < 0
\]

for \( 1 \leq i \leq m \).

**Proof.** The inequalities \( |u_i(x_k; \mu_k)| \leq 1, 1 \leq i \leq m \), and the last two relations follow immediately from (11).

(a) Since (29) holds, we can write

\[
B(x_{k+1}; \mu_{k+1}) - B(x_k; \mu_k) = (B(x_{k+1}; \mu_{k+1}) - B(x_{k+1}; \mu_k)) + (B(x_{k+1}; \mu_k) - B(x_k; \mu_k)) \leq -L(\mu_{k+1} - \mu_k) + (B(x_{k+1}; \mu_k) - B(x_k; \mu_k)),
\]

which together with (29), (26) and Lemma 5 implies

\[
B \leq \lim_{k \to \infty} B(x_k; \mu_k) \leq B(x_1; \mu_1) - L \sum_{k=1}^{\infty} (\mu_{k+1} - \mu_k) + \sum_{k=1}^{\infty} (B(x_{k+1}; \mu_k) - B(x_k; \mu_k)) \leq B(x_1; \mu_1) + L\overline{\pi} + \sum_{\rho(d_k) \geq \rho} (B(x_{k+1}; \mu_k) - B(x_k; \mu_k)) \leq B(x_1; \mu_1) + L\overline{\pi} - C \sum_{\rho(d_k) \geq \rho} \mu_k \left\| \tilde{g}_k \right\|^2,
\]

where

\[
B = \min_{0 \leq \mu \leq \overline{\pi}} 2m\mu(1 - \log(2\mu)) \geq 2m\overline{\pi}(1 - \log(2\overline{\pi}))
\]

(see (28)) and \( \left\| \tilde{g}_k \right\| = \min_{1 \leq j \leq k} \left\| g(x_j; \mu_j) \right\| \). If \( \liminf_{k \to \infty} \left\| g(x_k; \mu_k) \right\| = 0 \) was not satisfied, then a number \( \varepsilon > 0 \) would exist such that

\[
\left\| \tilde{g}_k \right\| \geq \varepsilon \quad \forall k \in \mathbb{N}.
\]

Then, using the last proved inequality, we obtain

\[
B(x_1; \mu_1) + L\overline{\pi} - B \geq C\varepsilon^2 \sum_{\rho(d_k) \geq \rho} \mu_k \geq C\varepsilon^2 \sum_{k \in K} \mu_k \geq \frac{C\varepsilon^2}{\tau} \sum_{k \in K} \left\| g(x_k; \mu_k) \right\|^2,
\]

where \( K \) is the infinite set of indices defined in Lemma 5. Thus \( \left\| g(x_k; \mu_k) \right\| \xrightarrow{K} 0 \) which is in a contradiction with (30).

(b) Using (9) and (10), one has \( z_i^2(x_k; \mu_k) - f_i^2(x_k) \leq 2\mu_k(2\mu_k + F) \). Thus \( z_i^2(x_k; \mu_k) - f_i^2(x_k) \to 0 \) as \( \mu_k \to 0 \). \( \square \)
Corollary 1. Let the assumptions of Theorem 1 be satisfied and the sequence \( \{x_k\}_{k=1}^{\infty} \) be bounded (either \( \mathcal{L}(F) \) in Assumption 1 is compact or Assumption 2 holds). Then there is a cluster point \( x \in \mathbb{R}^n \) of the sequence \( \{x_k\}_{k=1}^{\infty} \) that satisfies KKT conditions (3), where \( u \in \mathbb{R}^m \) is a cluster point of the sequence \( \{u(x_k;\mu_k)\}_{k=1}^{\infty} \).

Now we return to the case when \( \varepsilon > 0 \) and \( \mu > 0 \). The following lemma specifies a precision with which the KKT conditions are satisfied if Algorithm 1 terminates.

Theorem 2 Let Assumption 3 be satisfied. If Algorithm 1 terminates in the \( k \)-th iteration, then
\[
\left\| \sum_{i=1}^{m} u_i(x_k;\mu_k)g_i(x_k) \right\| \leq \varepsilon,
\]
and
\[
z_i(x_k;\mu_k) - |f_i(x_k)| \leq 2\mu, \quad |u_i(x_k;\mu_k)| \leq 1,
\]
\[
\left| u_i(x_k;\mu_k) - \frac{f_i(x_k)}{|f_i(x_k)|} \right| \leq \frac{2\mu}{|f_i(x_k)|}
\]
for \( 1 \leq i \leq m \).

Proof. The first inequality is a consequence of the termination condition (Step 2 of Algorithm 1). The second one follows from (10), since
\[
z_i(x_k;\mu_k) = \mu_k + \sqrt{\mu_k^2 + f_i^2(x_k)} \leq 2\mu + |f_i(x_k)|
\]
(\( \mu_k = \mu \) if Algorithm 1 terminates). The third inequality follows immediately from (11) and the last inequality is a consequence of the second one, since (11) implies
\[
\left| u_i(x_k;\mu_k) - \frac{f_i(x_k)}{|f_i(x_k)|} \right| = \left| \frac{f_i(x_k)}{z_i(x_k;\mu_k)} - \frac{f_i(x_k)}{|f_i(x_k)|} \right| = \frac{z_i(x_k;\mu_k) - |f_i(x_k)|}{z_i(x_k;\mu_k)} \leq \frac{2\mu}{|f_i(x_k)|}.
\]

Theorem 2 demonstrates that the first three KKT conditions can be satisfied with a prescribed precision and indicates that the last one could be inaccurate if \( |f_i(x_k)| \) is small. This indication was confirmed by our computational experiments. Using \( \mu = 10^{-8} \), we obtained \( 1 - |u_i| \approx 10^{-8} \) for \( |f_i| \approx 1 \) and \( 1 - |u_i| \approx 10^{-2} \) for \( |f_i| \approx 10^{-6} \).

5 Computational experiments

The primal interior-point method was tested by using the two collections of 22 relatively difficult problems with an optional dimension chosen from [16], which can be downloaded (together with the above report) from \url{www.cs.cas.cz/~luksan/test.html} as
Test 14 and Test 15. The functions $f_i(x), 1 \leq i \leq m$, given in [16] serve for defining the objective function

$$F(x) = \sum_{1 \leq i \leq m} |f_i(x)|.$$  \hspace{1cm} (31)

We have used the parameters $\varepsilon = 10^{-6}, \mu = 10^{-8}, \delta = 0.9, \bar{\delta} = 1.1, \Box = 1000, \rho = 10^{-4}, \overline{p_1} = 0.1, \overline{p_2} = 0.9, \beta = 0.1, \overline{\beta} = 0.5, \varphi = 2.0, \tau = 0.01$ in Algorithm 1 as defaults (the step bound $\Box$ was sometimes tuned).

The first set of the tests concerns a comparison of the primal interior point method (using various trust-region and line-search strategies) with several other methods for sparse minimax optimization. Medium-size test problems with 200 variables were used. The results of computational experiments are reported in two tables, where only summary results (over all 22 test problems) are given. Here Method is the method used: T1 the primal interior-point method with Algorithm A and the Gill-Murray decomposition, T2 the primal interior-point method with Algorithm A and the Bunch-Parlett decomposition, T3 the primal interior-point method with Algorithm B and the Gill-Murray decomposition, LS the primal interior-point method with line search and restarts described in [15], IP the primal-dual interior point method described in [15], BV the bundle variable metric method described in [17]. All these methods were realized in two modifications: NM denotes the discrete Newton method with the Hessian matrix computed using the differences by the way described in [3] and VM denotes the variable metric method with the partitioned updates described in [11]. At the same time NIT is the total number of iterations, NFV is the total number of function evaluations, NFG is the total number of gradient evaluations, NR is the total number of restarts, NL is the number of problems, for which the lowest known local minimum was not found (even if parameters $\mu$ and $\Box$ were tuned), NF is the number of problems, for which no local minimum was found (either a premature termination occurred or the number of function evaluations exceeded the upper bound), NT is the number of problems for which parameters were tuned and Time is the total computational time in seconds.

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Table 2: Test 15 – 22 problems with 200 variables

The results introduced in the above tables indicate that the trust-region strategies are more efficient than the restarted line-search strategies in connection with the interior-point method for \( l_1 \) optimization. These observations differ from conclusions concerning the interior-point method for minimax optimization proposed in [15], where the matrix \( \nabla^2 B \) has a different structure. The trust-region interior-point method T1 is less sensitive to the choice of parameters and requires a lower number of iterations and a shorter computational time in comparison with the bundle variable metric method B proposed in [17]. Method T1 also finds the best known local minimum (if \( l_1 \) problems have several local solutions) more frequently (see the column NL in the above tables).

The second set of the tests concerns a comparison of the interior-point method, realized as the dog-leg method with the Gill-Murray decomposition, with the bundle variable metric method described in [17]. Large-scale test problems with 1000 variables are used. The results of computational experiments are given in Tables 3 and 4, where P is the problem number, NIT is the number of iterations, NFV is the number of function evaluations, NFG is the number of gradient evaluations and F is the function value reached. The last row of every table contains the summary results including the total computational time in seconds. The bundle variable metric method was chosen for the comparison, since it is based on a quite different principle and can also be used for the large sparse \( l_1 \) optimization.
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Table 4: Test 15 – 22 problems with 1000 variables

The results introduced in Tables 3 and 4 confirm conclusions following from the previous tables. The trust-region interior-point method seems to be more efficient than the bundle variable metric method in all indicators. Especially, the computational time is much shorter and also the number of the best known local minima attained is greater in the case of the trust-region interior-point method. We believe that the efficiency of the interior-point method could be improved by using a better procedure for the barrier parameter update.
References


