Superquadratically convergent methods for minimization functions

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Abstract
In the paper locally superquadratically convergent methods for minimization functions are considered. Threefold symmetric approximations to partial derivatives of the third order are constructed.

1. Introduction
Let \( f : D \subset R^n \rightarrow R \), \( f \in C^3(D) \), \( D \) - open set. We want to find \( x^* \in D \) such that \( \nabla f(x^*) = 0 \). For a given \( x_0 \in D \) the Newton method defines the sequence \( \{x_k\} \) in the following way

\[
\nabla^2 f(x_k)s_k = -\nabla f(x_k), \quad x_{k+1} = x_k + s_k, \quad k = 0,1,2,\ldots.
\]

If the matrix \( \nabla^2 f(x^*) \) is nonsingular then Newton method is locally quadratically convergent to \( x^* \), i.e. there exist \( c > 0 \) and \( \varepsilon > 0 \) such that, if \( \|x^* - x_0\| < \varepsilon \), then

\[
\|x_{k+1} - x^*\| \leq c\|x_k - x^*\|^2.
\]

To assure global convergence of the method one should consider a sequence

\[
x_{k+1} = x_k + t_k s_k, \quad t_k \in R, \quad k = 0,1,2,\ldots
\]

and the parameter \( t_k \) should satisfy the global convergence conditions. If the matrix \( \nabla^2 f(x^*) \) is singular, then the Newton method is divergent or at most linearly convergent to \( x^* \). To assure a great speed of convergence for singular problems one applies the method of the third rate of convergence: for a given \( x_0 \in D \) the sequence \( \{x_k\} \) is defined as

\[
x_{k+1} = x_k + s_k, \quad k = 0,1,2,\ldots
\]

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where $s_k$ is the solution of the system of quadratic equations

$$
\nabla f(x_k) + \nabla^2 f(x_k) s_k + \frac{1}{2} (\nabla^3 f(x_k)) s_k, s_k = 0.
$$

(5)

When the calculation of the operator $\nabla^3 f(x_k)$ is too expensive or is not attainable for computation then we propose a new class of the methods which are locally superquadratically convergent to $x^*$, i.e.

$$
\lim_{k \to +\infty} \frac{\|x_{k+1} - x^*\|^2}{\|x_k - x^*\|^2} = 0.
$$

(6)

Let $B_k = (B_{k1}^1, B_{k2}^2, \cdots, B_{kn}^n), B_{ki} \in \mathbb{R}^{n \times n}, B_k^i = (B_k^i)^T, i = 1, 2, \cdots, n$. The sequence $\{x_k\}$ is defined by (1.4) and

$$
\nabla f(x_k) + \nabla^2 f(x_k) s_k + \frac{1}{2} (B_k s_k, s_k) = 0.
$$

(7)

If the problem $\min_{x \in D} f(x)$ is regularly singular at $x^*$, i.e.

$$
det(\nabla^2 f(x^*)) = 0, \quad \|\nabla f(x)\| \geq c \|x - x^*\|^2, \quad c > 0, \quad x \in D,
$$

(8)

then the sequence $\{x_k\}$ defined by (1.4) and (1.7) is locally superlinearly convergent to $x^*$, if the operators $B_k$ are constructed in an adequate way. In this paper such algorithms are given.

### 2. The BFGS method

The DFP (Davidon [1], Fletcher and Powell [2]) method is very well known as the method of approximation to the Hessian $\nabla^2 f(x_k)$. This formula has the form

$$
B_{k+1} = B_k - \frac{B_k s_k s_k^T B_k + y_k y_k^T}{s_k^T B_k s_k}, \quad y_k = \nabla f(x_{k+1}) - \nabla f(x_k).
$$

(9)

The DFP formula, for nonsingular problems, guarantees local superlinear convergence of the method

$$
x_{k+1} = x_k + s_k, \quad B_k s_k = -\nabla f(x_k), \quad k = 0, 1, 2, \cdots
$$

(10)

We may use the DFP formula to approximate the operator $\nabla^3 f(x_k)$. Namely, let

$$
B_k = (B_{k1}^1, B_{k2}^2, \cdots, B_{kn}^n), B_{ki} \in \mathbb{R}^{n \times n}, B_k^i = (B_k^i)^T, i = 1, 2, \cdots, n
$$

(11)

and let $\nabla^2 f(x_k), y_k^i = \nabla^2 f(x_{k+1}) - \nabla^2 f(x_k)$. Then

$$
B_{k+1}^i = B_k^i - \frac{B_k^i s_k s_k^T B_k^i + y_k^i (y_k^i)^T}{s_k^T B_k^i s_k} (y_k^i)^T s_k, \quad i = 1, 2, \cdots, n.
$$

(12)
Note that the operators $B_{k+1}$ satisfy the equation
\[ B_{k+1}s_k = \nabla^2 f(x_{k+1}) - \nabla^2 f(x_k), \quad k = 0, 1, 2, \ldots \] (13)

Now, from the general theory for the systems of nonlinear equations [3], [4] local superquadratic convergence of the method results (4), (7) with the update (12). On the other hand, the DFP updates do not satisfy the following properties of the partial derivatives
\[ \frac{\partial^3 f(x)}{\partial x_i \partial x_j \partial x_l} = \frac{\partial^3 f(x)}{\partial x_i \partial x_j \partial x_l}, \quad i, j, l = 1, 2, \ldots, n. \] (14)

In this case, we say the operator $\nabla^3 f(x)$ is threefold symmetric (T-symmetric).

It is worth remarking that the operator $\nabla^3 f(x)$ has only $P(n) = \frac{1}{6} n(n+1)(n+2)$ different elements and the DFP approximations have $Q(n) = \frac{1}{2} n^2(n+1)$ different elements, which means that the BFGS formula is not adequate for approximation to $\nabla^3 f(x)$. In the next Section we give a new formula for the update of $B_k$ and $B_k$ will be T-symmetric.

3. New approximation to $\nabla^3 f(x)$

The approximation $B_k$ to $\nabla^3 f(x)$ satisfies secant equation (13) and operators $B_k$ should be threefold symmetric. If we take
\[ B_{k+1} = B_k + E, \] (15)

then
\[ ES_k = \nabla^2 f(x_{k+1}) - \nabla^2 f(x_k) - B_k s_k = Y. \] (16)

In that case we have to solve the problem
\[ \min \|E\|^2, \quad \|E\|^2 = \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{k=1}^{n} E_{ijk}^2 \] (17)
under constraints
\[ ES = Y, \quad s \in R^n, \quad Y \in R^{n \times n}, \quad Y = Y^T \] (18)
and
\[ E_{ijk} = E_{skj} = E_{jik} = E_{jks} = E_{skj} = E_{kji}, \quad i, j, k = 1, 2, \ldots, n. \] (19)

Remark. If we take another norm of the operator $E$, then we get another formula for the update $B_k$.

Let $\Lambda \in R^{n \times n}$. In our case the lagrangian has the form
\[ L(E, \Lambda) = \frac{1}{2} \|E\|^2 + \sum_{i=1}^{n} \sum_{j=1}^{n} \Lambda_{ij} \left( \sum_{k=1}^{n} E_{ijk} s_k - Y_{ij} \right). \] (20)
From this we have

\[ \frac{\partial L(E, \Lambda)}{\partial E_{pqr}} = E_{pq} + \Lambda_{pq} s_r = 0. \] (21)

The fact \( E_{pq} = E_{qp} \) implies \( \Lambda = \Lambda^T \). Since the operator \( E \) is threefold symmetric then equation (21) may be written as

\[ E_{pq} = -\frac{1}{3} (\Lambda_{pq} s_r + \Lambda_{pr} s_q + \Lambda_{qr} s_p) \quad \text{for} \quad 1 \leq p \leq q \leq r \leq n. \] (22)

Now, the equation \( Es = Y \) has the form

\[ \sum_{l=1}^{n} (\Lambda_{ql} s_l + \Lambda_{kl} s_l + \Lambda_{jl} s_l) s_l = -3Y_q, \quad 1 \leq i \leq j \leq n \] (23)

or is in the matrix form

\[ \Lambda \|s\|^2 + \Lambda ss^T + ss^T \Lambda = -3Y. \] (24)

Therefore

\[ s^T \Lambda s = -\frac{1}{\|s\|^2} s^T Y_s, \quad u = \Lambda s = \frac{1}{2\|s\|^2} (-3Y_s + \frac{s^T Y_s}{\|s\|^2} s). \] (25)

Finally

\[ \Lambda = -\frac{1}{\|s\|^2} (3Y + us^T + su^T). \] (26)

To calculate the new threefold symmetric update \( B_{k+1} = B_k + E \) we use the formulae (22), (25) and (26).

4. Remarks on the local superquadratic convergence of the method

At first we describe the proposed algorithm:

a) Let \( x_0 \in \mathbb{R}^n \) and \( B_0 = (B_1^0, B_2^0, \ldots, B_n^0) \) - threefold operator be given. Let \( k = 0 \),

b) Solve, using for example the Newton method, the system of quadratic equations

\[ \nabla f(x_k) + \nabla^2 f(x_k) s_k + \frac{1}{2} (B_k s_k, s_k) = 0, \]

c) Calculate \( x_{k+1} = x_k + s_k \), \( \nabla f(x_{k+1}) \), \( \nabla^2 f(x_{k+1}) \),

d) Update the operator \( B_k \) using the formulae from Section 3,

e) If a stop criterion is not satisfied, then \( k := k + 1 \) and return to point b.

To explain a character of convergence of the method we introduce some notations. Let
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\[ H_k = \frac{1}{2} \int_0^1 \nabla^3 f(x_k + t(x_{k+1} - x_k)) \, dt , \quad (27) \]

\[ L_k = \{ X \in R^{n \times n \times n} : Xs_k = \nabla^2 f(x_{k+1}) - \nabla^2 f(x_k) \} , \quad (28) \]

\[ Q = \{ X \in R^{n \times n \times n} : X \text{ is threefold symmetric operator} \} . \quad (29) \]

The set \( Q \) is linear subspace in \( R^{n \times n \times n} \) and \( H_k \in Q \). Applying Theorem 3.2.7 [5] we have

\[ H_k s_k = \nabla^2 f(x_{k+1}) - \nabla^2 f(x_k) , \quad (30) \]

which means that \( Q \cap L_k \) is a nonempty linear set. The proposed norm is generated by inner product, so the operator \( B_{k+1} \) is defined as the orthogonal projection of the operator \( B_k \) onto the set \( Q \cap L_k \), and from Pitagoras Theorem (see [3]) we get

\[ \| B_{k+1} - H_k \|^2 + \| B_k - B_{k+1} \|^2 = \| B_k - H_k \|^2 \quad k = 0, 1, 2, \ldots \quad (31) \]

The inequality \( \| B_{k+1} - H_k \| \leq \| B_k - H_k \| \) implies local linear convergence of the sequence \( \{ x_k \} \). From equations (31) it results additionally

\[ \sum_{k=0}^{\infty} \| B_{k+1} - B_k \|^2 < \infty . \quad (32) \]

The last inequality and the secant equation (13) assure local superquadratic convergence of the proposed algorithm [4].

References


