Original Research Article

Performance of New Line Search Methods with Three-Term Hybrid Descent Method for Unconstrained Optimization Problems

ABSTRACT

In this paper, we demonstrate the performance of new line search methods with three-term hybrid descent method for the solution of unconstrained optimization problems. The techniques advanced the sustainable range of step-length to a broader level than the previous ones and give a suitable initial step-length at each steps of iterations. The global convergence rate of the new line with three-term hybrid descent method search is carried studied. Some numerical results through performance profile shows that among the new search method modified Wolfe line search method in CPU time and iterations is best in practical computation.
Keywords: Quasi-Newton method, search direction, step-length, global convergence, performance profile.

1. Introduction

Considering an unconstrained optimization problem

$$\min_{x\in\mathbb{R}^n} f(x). \tag{1.1}$$

where R^n is an n-dimensional Euclidean space and $f : R^n \to R$ is continuously differentiable.
The solution of (1.1) require using an iterative methods with initial starting point x_0 to generate a sequence of points $\{x_k\}$, $k = 1, 2, 3...n$, and show progressive approximations to the required solution by applying the formula

$$x_{k+1} = x_k + \alpha_k d_k \qquad k = 0, 1, ...n. \tag{1.2}$$

Where x_k is the current iterate, d_k the search direction, and α_k the step-length. Let (x^*) be a minimizer of (1.1) and thus be a stationary point that satisfies $g(x^*) = 0$. We denote $f(x_k)$ by f_k, f_{x^*} by f^*, and $\nabla f(x_k)$ by g_x respectively. The line search method required two step at each iterations. First is to obtain a search direction d_k and second is to select the step-length α_k along the search direction. On the other hand, thed_k is typically needed to satisfy the descent condition $g_k^T d_k < 0$ which guarantees that d_k is a descent direction of $f(x)$ at x_k. It has been proved that search direction perform an essential role in line search techniques and that the step-length methods mainly guarantee global convergence.
The following condition holds in order to obtain the global convergence of the line search methods.

$$-\frac{g_k^T d_k}{||g_k||.||d_k||} \geq c. \tag{1.3}$$

where $c \in (0, 1]$ is a constant. The condition (1.3) is sometimes called angle property.
The different method of approaches to select d_k and α_k yield different convergence properties, and also for the step-length ensure that the sequence of iterates x_k defined by (1.2) globally converges with some rate of convergence. There are two ways of determine the values of the step-length; By using an exact line search and an inexact line search.
For exact line search, α_k is obtained by using the formula

$$\alpha_k = \arg\min_{\alpha>0}(f(x_x + \alpha_k d_k)). \tag{1.4}$$

However, it is complex and often problematic to find in practical computation. Therefore, the inexact line search has been introduced by previous researchers: (Armijo, 1966), (Wolfe, 1969), and (Goldstein, 1965) to overcome this challenge. Recently, (Yuan, Wei, & Yang, 2019) proposed the global convergence of some conjugate gradient method with inexalt line search, (Berahas, Cao, & Scheinberg, 2021) analyse the global convergence of some line search methods, (Hosseini Dehmiry, 2020) show the global convergence of quasi family under conjugate technique, (Yuan, Sheng, Wang, Hu, & Li, 2018) the global convergence under quasi family, (Masmali, Salleh, & Alhawarat, 2021) proposed the global convergence properties on a large scale problem, and (Wang, Yin, & Zeng, 2019) show the global convergence of non-convex optimization problem.
This work focused on new inexact line search rule called modified line search rules that advanced the scope of appropriate step-length and give a good initial step-length at each iteration.
Modified Armijo Rule.
Set scalar $l_k > 0, \beta \in (1, 0)$, $\sigma \in (0, \frac{1}{2})$, and set $S_k = -\frac{g_k^T d_k}{l_k||d_k||^2}$. Let α_k be the largest α in $\{s_k, \beta s_k, \beta^2 s_k....\}$ such that

$$f_k - f(x_k + \alpha d_k) \geq \sigma\alpha||d_k||w_k(\alpha), \tag{1.5}$$

Modified Goldstein Rule.
A fixed scalar $\sigma = (0, \frac{1}{2})$ is selected and α_k is chosen to satisfy

$$-(1-\sigma)\alpha_k g_k^T d_k \geq f_k - f(x_k + \alpha_k d_k) \geq \sigma\alpha_k||d_k||w_k(\alpha_k), \tag{1.6}$$

Modified Wolfe Rule.
The step α_k is chosen to satisfy

$$f_k - f(x_k + \alpha_k d_k) \geq \sigma\alpha_k||d_k||w_k(\alpha_k)$$

and

$$g(x_k + \alpha_k d_k)^T d_k \geq y g_k^T d_k. \tag{1.7}$$

where σ and y are some scalars with $\sigma \in (0, \frac{1}{2})$ and $y \in (0, 1)$ for $k = 0, 1, 2, \ldots n$. Then, the sequence of $\{x_k\}_{k=0}^{\infty}$ converges to the optimal point x^* which minimizes $f(x)$. Hence, modified Armijo, Goldsten, and Wolfe line search methods are used in this research associated with three-term hybrid descent search direction.
This paper is organized as follows; In section (2), I illustrate and discussed extensively the importance of search direction in iterative method. The new three-term hybrid method and its convergence analysis are discussed in section (3). Numerical results and discussion are given in section (4). The paper ends with a short conclusion in section (5).

2. The Search Direction

In an iterative method of solving an unconstrained optimization problem, search direction is most important and essential which includes: conjugate gradient method, Newton method, and quasi-

Newton method. Several of the techniques used in solving unconstrained optimization problem relies solely on the results of search direction d_k. The conjugate gradient (CG) approach contain a class of unconstrained optimization algorithms with a properties of low memory, easy computation and global strong convergence, making them efficient for solving large-scale problems in the form of $min_{x\in\mathbb{R}^n} f(x)$ with the differentiable non-linear function $f : R^n \to R$. The CG method is also essential in finding the minimum value of functions of an unconstrained optimization problems. (Stiefel, 1952) starts a CG method of solving a linear system of equations with a symmetric positive definite coefficient matrix for minimizing a strictly convex quadratic function. After, (Fletcher & Reeves, 1964) used the CG method to solve unconstrained optimization problems. Recently, CG methods is becoming more popular iterative methods to solve large-scale unconstrained optimization problems, since they do not required the storage of matrices (Hanke, 2017; Meurant, 2020; Alhawarat, Alhamzi, Masmali, & Salleh, 2021; Livieris, Tampakas, & Pintelas, 2018; Waziri, Ahmed, & Sabi'u, 2020; Yuan, Wang, & Sheng, 2020; Hassan, Abdullah, & Jabbar, 2019). The search direction of conjugate gradient methods is defined by the following:

$$d_k = \begin{cases} -g_k & k = 0, \\ -g_k + \beta_k d_{k-1} & k \geq 1. \end{cases} \tag{2.1}$$

where $g_k = \nabla f(x_k)$ and β_k is known as the CG coefficient. There are many ways to calculate β_k and some well-known formulae are.

$$\begin{aligned} \beta_k^{FR} &= \frac{g_k^T g_k}{||g_{k-1}||^2}, \\ \beta_k^{PR} &= \frac{g_k^T (g_k - g_{k-1})}{||g_{k-1}||^2}, \\ \beta_k^{HS} &= \frac{g_k^T (g_k - g_{k-1})}{(g_k - g_{k-1})^T d_{k-1}}, \\ \beta_k^{BAN} &= \frac{-g_k^T (g_k - g_{k-1})}{g_{k-1}^T (g_k - g_{k-1})}, \\ \beta_k^{HZ} &= \left(y_k - \frac{(2d_k(\|y_k\|)^2)}{(d_k y_k)} \right)^T \left(\frac{g_{k+1}}{(d_k^T y_k)} \right). \end{aligned}$$

where g_k and g_{k-1} are gradients of $f(x)$ at the points x_k and x_{k-1} and $y_k = g_k - g_{k-1}$ respectively. While $||.||$ is a norm of vectors and d_{k-1} is a direction for the previous iteration. The above corresponding coefficients are known as (Fletcher and Reeves, 1964), (Polak and Ribiere, 1969) and (Hestenes and Stiefel, 1952) and (Zhang, Zhou, & Li, 2007; Narushima, Yabe, & Ford, 2011; Andrei, 2013; Liu & Li, 2014; Dong, Liu, & He, 2015; Moyi & Leong, 2016). Recently, (Kobayashi, Narushima, & Yabe, 2017; Gao & He, 2018; Bojari & Eslahchi, 2020; Baluch, Salleh, & Alhawarat, 2018; ABDULLAH & JAMEEL, 2019) proposed three-term conjugate gradient methods which always satisfy the sufficient descent condition.

$$g_k^T d_k \leq -\bar{c}||g_k||^2 \qquad for \quad all \quad k = 0, 1, 2...n. \tag{2.2}$$

and a positive constant $\bar{c}$, independently of line searches. They proposed the modified FR method defined by

$$d_k = -\bar{\theta_k} g_k + \beta^{FR} d_{k-1}$$

Where $\bar{\theta_k} = \frac{d_{k-1}^T y_{k-1}}{||g_{k-1}||^2}$. Since this search direction satisfies $g_k^T d_k < -||g_k||^2$ for all k, it can be written by the three-term form:

$$d_k = -g_k + \beta^{FR} d_{k-1} - \theta_k^1 g_k, \tag{2.3}$$

where $\theta_k^1 = \frac{g_k^T d_{k-1}}{||g_{k-1}||^2}$. They also proposed the modified PR methods and the modified HS method, which are respectively given by

$$d_k = -g_k + \beta^{PR} d_{k-1} - \theta_k^{(2)} y_{k-1}, \tag{2.4}$$

$$d_k = -g_k + \beta^{HS} d_{k-1} - \theta_k^{(3)} y_{k-1}, \tag{2.5}$$

Where $\theta_k^{(2)} = \frac{g_k^T d_{k-1}}{||g_{k-1}||^2}$ and $\theta_k^{(3)} = \frac{g_k^T d_{k-1}}{d_{k-1}^T y_{k-1}}$. Cheng gave another modification of PR method:

$$d_k = -g_k + \beta_k^{PR}(I - \frac{g_k g_k^T}{g_k^T g_k})d_{k-1} = -g_k + \beta_k^{PR} d_{k-1} - \beta_k^{PR} \frac{g_k^T d_{k-1}}{g_k^T g_k} g_k. \tag{2.6}$$

They obtained their global convergence properties under appropriate line searches. The recent modification can be seen (Masmali et al., 2021; Liu, Feng, & Zou, 2018; Liu & Du, 2019; Abubakar, Kumam, Ibrahim, Chaipunya, & Rano, 2021; Bojari & Eslahchi, 2020). We observe that these approach always satisfy $g_k^T d_k = -||g_k||^2 < 0$ for all k, which indicate the sufficient descent condition with $\bar{c} = 1$.
In quasi-Newton family, the search direction is the solution of linear system

$$d_k = -H_k g_k. \tag{2.7}$$

where H_k is an approximation of Hessian. Initial matrix H_0 is selected by the identity matrix, which thereafter updates by an update formula. There are a few update formulae that are widely used like Davidon-Fletcher-Powell(DFP), BFGS, and Broyden family formula. This study employs a BFGS formula in a classical algorithm and the new hybrid method. The update formula for BFGS is

$$H_{k+1} = H_k - \frac{H_k s_k s_k^T H_k}{s_k^T H_k s_k} + \frac{y_k y_k^T}{s_k^T y_k}, \tag{2.8}$$

with $s_k = x_k - x_{k+1}$ and $y_k = g_k - g_{k-1}$. The approximation that the Hessian must fulfil is

$$H_{k+1} s_k = y_k, \tag{2.9}$$

This condition is essential to hold for the updated matrix H_{k+1}. Note that it is only feasible to fulfil the equations if

$$s_k^T y_k > 0. \tag{2.10}$$

which is called the curvature condition.

3. The Proposed Three-Term Method

The modification on three-term approach have been proposed by many researchers; One of the research is by Ludwig (Ludwig, 2007) which is a hybrid between quasi-Newton methods with Gauss-siedel method to solve the system of linear equation. Then, Luo et.al (Luo, Tang, & Zhou, 2008) suggested the new hybrid method which can solve the system of non-linear equations by combining quasi-Newton method with chaos optimization. Besides, Han and Newman (Han & Neumann, 2003) combine the Quasi-Newton methods and Cauchy descent method to solve unconstrained optimization problems and recognized as quasi-Newton-SD method. Also Ibrahim et.al(Ibrahim, Mamat, & Leong, 2014) proposed BFGS-CG method which is between quasi-Newton and conjugate gradient method and come out with this search direction.

$$d_k = \begin{cases} -H_k g_k & k = 0, \\ -H_k g_k + \eta(-g_k + \beta_k d_{k-1}) & k \geq 1. \end{cases}$$

where $\eta > 0$ $\quad \beta_k = \frac{g_k^T g_k - 1}{g_k^T d_k - 1}$

Hence, the modification on Quasi-Newton by previous researchers spawned the new idea on hybrid; the classical method to yield the new hybrid method. Hence, a new hybrid search direction which combines the concept of search direction of quasi-Newton and conjugate gradient method is created. It yields a new search direction of hybrid method which is known as Three-term BFGS-CG method. Search direction for Three-term BFGS-CG method

$$d_k = \begin{cases} -H_k g_k & k = 0, \\ -H_k g_k + \eta(-g_k + \beta_k d_{k-1} - \beta_k \frac{g_k^T d_{k-1}}{g_k^T g_k} g_k) & k \geq 1. \end{cases} \tag{3.1}$$

where $\eta > 0$ $\quad \beta_k = \frac{g_k^T g_k - 1}{g_k^T d_k - 1}$

Hence, the complete algorithms for BFGS, (CG-HS, CG-PR, CG-FR), and Three-Term BFGS-CG method will be arranged in Algorithm(16), Algorithm(17) and (18) respectively.

Algorithm(1) Modified Armijo line search for Three-term BFGS-CG.

Step 1. Given a starting point x_0 and $H_o = I_n$, choose values for s, β, and σ. Set $k = 1$
Step 2. Terminate if $||g(x_{k+1})|| < 10^{-6}$ or $k \leq 1000$
Step 3. Calculate the search direction by (3.1).
Step 4. Calculate the step length α_k by (1.5).
Step 5. Compute the difference between $s_k = x_k - x_{k-1}$ and $y_k = g_k - g_{k-1}$
Step 6. Update H_{k+1} by (12) to obtain H_k
Step 7. Set $k = k + 1$ and go to step 2.

Algorithm(2) Modified Goldstein line search for Three-term BFGS-CG method .

Step 1. Giving a starting initial point x_0 and choose values for s, β, and σ. Set $k = 1$
Step 2. Terminate if $||g(x_{k+1})|| < 10^{-6}$ or $k \leq 1000$.
Step 3. Calculate the search direction by (3.1)
Step 4. Calculate the step size α_k by (1.6)
Step 5 Compute the difference $s_k = x_k - x_{k-1}$ and $y_k = g_k - g_{k-1}$
Step 6. Update H_{k+1} by (2.8) to obtain H_k.
Step 7.Set $k = k + 1$ and go to step 2.

Algorithm(3) Modified Wolfe line search for Three-term BFGS-CG method.

Step 1. Given a starting point x_0 and $H_o = I_n$, choose values for s,β, and σ. Set $k = 1$.
Step 2. Terminate if $||g(x_{k+1})|| < 10^{-6}$ or $k \leq 1000$.
Step 3. Calculate the search direction by(3.1)
Step 4. Calculate the step length α_k by (1.7).
Step 5. Compute the difference between $s_k = x_k - x_{k-1}$ and $y_k = g_k - g_{k-1}$.
Step 6. Update H_{k+1} by (2.8) to obtain H_k.
Step 7. Set $k = k + 1$ and go to step 2.

Based on Algorithm (1), (2), and (3), we assume that every search direction d_k satisfied the descent condition $g_k^T d_k < 0$.

Hence, we need to make a few assumption based on the objective function
Assumption 3.1
H1: The objective function f is twice continuously differentiable.
H2: The level set L is convex. Moreover, positive constants c_1 and c_2 exist, satisfying

$$c_1||z||^2 \leq z^T F(x)z \leq c_2||z||^2. \tag{3.2}$$

for all $z \in R^n$ and $x \in L$ where $f(x)$ is the Hessian matrix of f.
H3: The Hessian matrix is Lipschitz continuous at the point x^* that is, there exist the positive constant c_3 satisfying

$$||g(x) - g(x^*)|| \leq c_3||x - x^*||. \tag{3.3}$$

for all x in a neighbourhood of x^*
Theorem 3.2 (see[6])
Let $\{B_k\}$ be generated by BFGS formal (2.8), where B_k is symmetric and positive definite, and $y_k^T s_k > 0$ for k. Furthermore, assume that $\{s_k\}$ and $\{y_k\}$ are such that

$$\frac{||(y_k - G_*)s_k||}{||s_k||} \leq \epsilon_k. \tag{3.4}$$

for some symmetric and definite matrix $G(x^*)$ and for some sequence ϵ_k with the property. $\sum_{k=1}^{\infty} \epsilon_k < \infty$. Then

$$lim_{k\to\infty} \frac{||(B_k - G_* d_k)||}{||d_k||} = 0. \tag{3.5}$$

and the sequence $||\{B_k\}||$, $||\{B_k^{-1}\}||$ are bounded.
Theorem(3.3). Global convergence.
Suppose that Assumption (3.1) and Theorem(3.2) hold. Then

$$\lim_{k\to\infty} ||g_k||^2 = 0. \tag{3.6}$$

Proof.
from the condition $g_k^T d_k < 0$, we see that

$$g_k^T d_k = -g_k^T B_k^{-1} g_k + \eta g_k^T (-g_k + \beta_k d_{k-1} - \beta_k \frac{g_k^T d_{k-1}}{g_k^T g_k} g_k), \tag{3.7}$$

$$= -g_k^T B_k^{-1} g_k + \eta(-g_k^T g_k + \frac{g_k^T g_{k-1}}{g_k^T d_{k-1}} g_k^T d_{k-1} - \frac{g_k^T g_{k-1}}{g_k^T d_{k-1}} \frac{g_k^T d_{k-1}}{g_k^T g_k} g_k^T g_k), \tag{3.8}$$

$$= -g_k^T B_k^{-1} g_k + \eta(-g_k^T g_k + g_k^T g_{k-1} - g_k^T g_{k-1}), \tag{3.9}$$

then

$$g_k^T d_k = -g_k^T B_k^{-1} g_k + \eta(-||g_k||^2), \tag{3.10}$$

$$\leq -\lambda_k ||g_k||^2 + \eta(-||g_k||^2), \tag{3.11}$$

$$g_k^T d_k \leq c_1 ||g_k||^2, \tag{3.12}$$

where $c_1 = -(\lambda_k + \eta)$ which is bounded away from zero. Hence, from the Armijo line search condition, we have that .

$$f_k - f_{k+1} \leq \sigma \alpha_k g_k^T d_k, \tag{3.13}$$

$$\leq \sigma \alpha_k c_1 ||g_k||^2, \tag{3.14}$$

holds for all k. Since f_k is decreasing and the sequence $\{f_k\}$ is bounded below by H2, we have that

$$\lim_{k\to\infty} (f_k - f_{k+1}) = 0, \tag{3.15}$$

Hence, this (3.14) and (3.15) imply

$$\lim_{k\to\infty} ||g_k||^2 = 0. \tag{3.16}$$

Test Problems	n-dimension	Sources
Powell badly scaled	2	More et al.
Beale	2	More et al.
Biggs Exp	6 6	More et al.
Chebyquad	4 6	More et al.
Colville polynomial	4	Michalewicz
Variably dimensioned	4, 8	More et al.
Freudenstein and Roth	2	More et al.
Goldstein price polynomial	2	Michalewicz
Himmelblau	2	Andrei
Penalty	1 2 4	More et al.
Extended Powell singular	4, 8	More et al.
Extended Rosenbrock	2, 10, 100, 200, 500, 1000	Andrei
Arwhead	10,50,100,500,1000	Andrei
PSC 1	2	More et al.
Six-hump camel back polynomial	2	Michalewicz
Extended Cliff	2, 4, 10, 100, 200, 500, 1000	Andrei
Extended Hiebert	2, 4, 10, 100, 200, 500, 1000	Andrei
Extended EP1	2,4,10	Michalewicz
Raydan	1 2, 4	Andrei
Raydan	2 2, 4	Andrei
Diagonal	3 2	Andrei
Cube	2, 10, 100, 200	More et al.

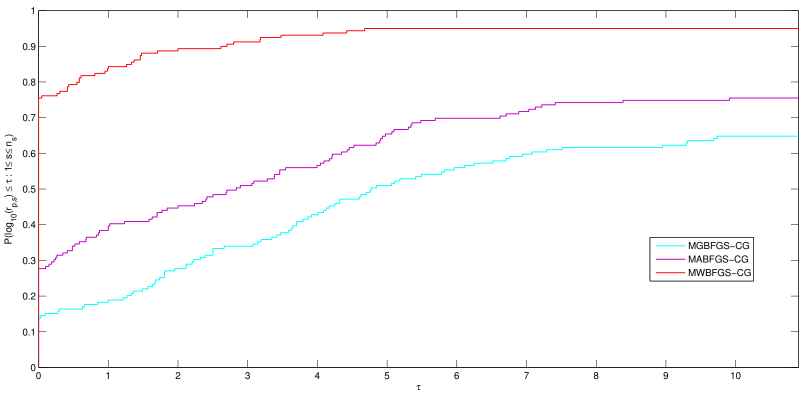

Figure 1: Performance Profile in a log_{10} scale based on iteration

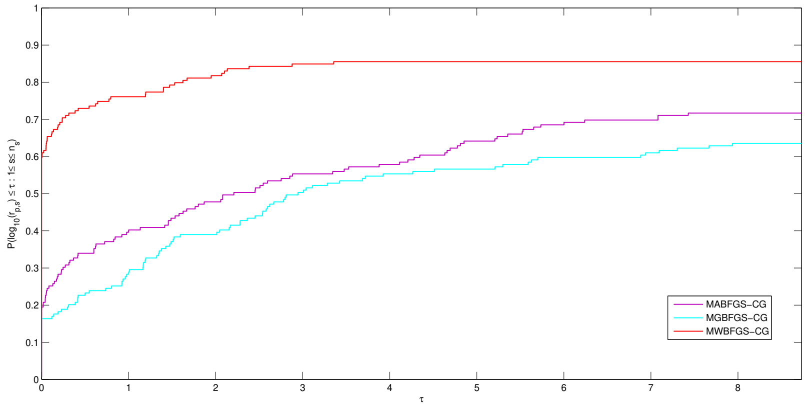

Figure 2: Performance Profile in a log_{10} scale based on CPU time

4. Numerical Results and Discussion

In this section, we used a set of some selected unconstrained optimization problems from the CUTEr suite to analyse the performance of several new line search methods used with three-term hybrid descent method. Each of the test problems is tested with dimensions varying from 2 to 1000. For each of the test problems, the initial point x_0 will take further away from the minimum point. In doing so, leads us to test the global convergence properties and the robustness of the method. For the Modified Armijo line search, Modified Goldstein line search and Modified Wolfe line search we use $\sigma = (o, \frac{1}{2})$, the stopping criteria used are $||g_k|| \leq 10^{-6}$ and the number of iterations exceeds a limit of 10,000. Performance profile were drawn for the above methods. In general $p(\tau)$ is the fraction of problems with performance ratio τ; thus, a solver with high values of $p(\tau)$ is preferable. The implementation, numerical tests was performed on Matlab 2021a languages. Performance profiles of methods are illustrated in Figures 1 and 2. The performance profile seeks to find how well the solvers perform relative to the other solvers on a set of problems. From Figures 1 and 2, three-term hybrid modified wolfe line search approach has the best performance since it can solve (97%) of the test problems compared with the three-term hybrid modified Armijo line search(77%) and three-term hybrid modified Goldstein line search(62%).

5. Conclusion

In summary, we have presented performance of several line search methods used with three-term BFGS-CG Method descent search for solving unconstrained optimization problems which guaranteed sufficient descent condition, and was able to deduce that modified wolfe perform best on performace profile. Forming an hybrid method out of the existing methods is more efficient especially when the strength of the component are the target of the hybridization.

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