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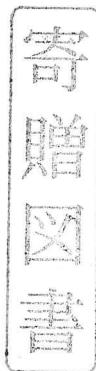
# Global Optimization in Action

*Continuous and Lipschitz Optimization:  
Algorithms, Implementations and Applications*

by

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filename'. This step typically needs the (automatic) loading of the output file(s) filename.OUT and filename.SUM. For instance, the sample points generated by the optimizer (their two-dimensional projection into a specified subspace), or a graph of the best function value found versus actual number of steps, etc., may follow. After inspecting these graphs, control is returned again to the main menu.

#### Quit

Typing 'Q' at the main menu, the LGO program system application is terminated, and the program returns to the operating system (DOS) from which LGO was called.

#### 3.4.4 Illustrative Test Results

To illustrate the use of the LGO program system, the solution of two 50-variable test problems of the form (3.4.1) will be discussed below.

##### Example 1

In the first example, the objective function  $f$  is defined as follows.

$$f(x) = f_1(x) + f_2(x) + f_3(x), \quad \text{in which} \quad (3.4.2)$$

$$f_1(x) = \sum_{i=1}^n ix_i^2$$

$$f_2(x) = \sum_{i=1}^n (x_{i-1} + 5 \sin x_i + x_{i+1}^2)^2$$

$$f_3(x) = \sum_{i=1}^n \ln^2(1 + |i \sin^2 x_{i-1} + 2x_i + 3x_{i+1}|).$$

(By definition, in (3.4.2)  $x_0 = x_n$  and  $x_{n+1} = x_1$ ;  $\ln(\cdot)$  denotes the natural logarithm function.)

Let us make a few comments related to the function (3.4.2). The first sum,  $f_1$ , consists of the simplest possible quadratic terms. Nevertheless—due to the multipliers  $i$  of the individual terms, in case of large  $n$ —the resulting sum will become 'badly scaled': specifically, the rate of the largest and smallest axes in the ellipsoid level sets of the function  $f_1$  equals  $\sqrt{n}$ . Note also that component  $f_1$  serves to model the situation in which the

'far side' of the 'vaguely defined' search region  $[a, b]$  contains only inferior solutions: this is typical in many well-posed global optimization problems of the form (3.4.1).

The two other component functions of  $f$  (the sums  $f_2$  and  $f_3$ ) model a noise structure superimposed on  $f_1$ , leading to a multiextremal function  $f$  in  $n$  variables. The function  $f_2$  is a combination of embedded linear, trigonometric and quadratic terms, in simple quadratic function addenda. The oscillation amplitude of the trigonometric term is magnified by its multiplier factor. Finally, the function  $f_3$  is made up by logarithmic terms, with embedded trigonometric and linear arguments. All embedded terms in  $f_2$  and  $f_3$  depend on three subsequent component of the vector  $x$ . One can also observe that the noise terms become relatively more significant in a closer neighbourhood of the optimal solution. In summary, although function  $f$  defined by (3.4.2) is not very complicated, it surely has 'somewhat tricky' nonlinearities and multiextremal structure, and in case of a large initial region of uncertainty (given by  $[a, b]$ ) most local scope methods would probably have difficulties in finding the global solution—the zero vector.

$$\begin{aligned}
 a(1) &= -8.8 & a(11) &= -7.8 & a(21) &= -8.5 & a(31) &= -3.5 & a(41) &= -5.5 & (3.4.3) \\
 b(1) &= 1.4 & b(11) &= 3.2 & b(21) &= 7.2 & b(31) &= 1.9 & b(41) &= 2.2 \\
 a(2) &= -6.2 & a(12) &= -5.2 & a(22) &= -1.2 & a(32) &= -6.2 & a(42) &= -3.2 \\
 b(2) &= 0.9 & b(12) &= 3.9 & b(22) &= 4.9 & b(32) &= 3.9 & b(42) &= 4.9 \\
 a(3) &= -8.7 & a(13) &= -6.1 & a(23) &= -5.7 & a(33) &= -7.1 & a(43) &= -4.3 \\
 b(3) &= 1.7 & b(13) &= 1.8 & b(23) &= 3.5 & b(33) &= 3.5 & b(43) &= 7.8 \\
 a(4) &= -7.7 & a(14) &= -2.7 & a(24) &= -7.7 & a(34) &= -7.7 & a(44) &= -4.7 \\
 b(4) &= 0.8 & b(14) &= 4.2 & b(24) &= 1.5 & b(34) &= 4.8 & b(44) &= 2.5 \\
 a(5) &= -3.2 & a(15) &= -5.6 & a(25) &= -8.6 & a(35) &= -5.6 & a(45) &= -3.6 \\
 b(5) &= 5.3 & b(15) &= 3.3 & b(25) &= 5.3 & b(35) &= 2.3 & b(45) &= 8.3 \\
 a(6) &= -3.5 & a(16) &= -7.1 & a(26) &= -9.5 & a(36) &= -6.5 & a(46) &= -4.5 \\
 b(6) &= 7.9 & b(16) &= 2.9 & b(26) &= 6.8 & b(36) &= 2.8 & b(46) &= 1.9 \\
 a(7) &= -5.1 & a(17) &= -2.1 & a(27) &= -5.1 & a(37) &= -5.1 & a(47) &= -4.1 \\
 b(7) &= 8.7 & b(17) &= 6.7 & b(27) &= 3.7 & b(37) &= 8.7 & b(47) &= 1.7 \\
 a(8) &= -2.2 & a(18) &= -5.2 & a(28) &= -6.7 & a(38) &= -3.2 & a(48) &= -7.2 \\
 b(8) &= 4.7 & b(18) &= 3.7 & b(28) &= 1.7 & b(38) &= 1.7 & b(48) &= 3.2 \\
 a(9) &= -9.1 & a(19) &= -4.1 & a(29) &= -4.1 & a(39) &= -5.1 & a(49) &= -4.1 \\
 b(9) &= 3.8 & b(19) &= 2.8 & b(29) &= 1.8 & b(39) &= 1.8 & b(49) &= 1.8 \\
 a(10) &= -6.3 & a(20) &= -7.3 & a(30) &= -4.3 & a(40) &= -3.3 & a(50) &= -5.3 \\
 b(10) &= 1.7 & b(20) &= 4.7 & b(30) &= 6.7 & b(40) &= 7.7 & b(50) &= 1.3
 \end{aligned}$$

In the test example, we chose  $n = 50$ . The components of the lower and upper bound vectors  $a$  and  $b$  are given in (3.4.3). (The numerical values

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and results are directly cited from the output files LGOTEST.OUT and LGOTEST.SUM, except for minimal necessary text editing.)

The value of the objective function (3.4.2) at the lower and the upper bound vectors equals  $f(a) = 106613.50$ , and  $f(b) = 80112.91$ . These values indicate that the Lipschitz constant will be quite large, when  $[a, b]$  is scaled—automatically, by the optimization algorithm—into the 50-dimensional unit interval.

To minimize function (3.4.2) on  $[a, b]$  of (3.4.3) by the LGO program system, the maximal number of global and local phase search steps was chosen as  $\max_g = 2 \cdot 10^5$  and  $\max_l = 10^5$ , respectively. To put these ‘large’ values into proper perspective, observe that a 50-dimensional interval has, for example,  $2^{50} > 10^{15}$  vertices: hence, the above values  $\max_g$  and  $\max_l$  can be considered quite modest. The other LGO parameters were chosen in such a manner that  $\max_g$  and  $\max_l$ , in effect, served to control the program execution. It should be noted at this point that—since these stopping criteria are not checked at every single function evaluation—the actual number of global/local search steps may slightly exceed the stated bounds  $\max_g / \max_l$ .

The results of the optimization run are summarized below.

### Global Search Phase

*Number of function evaluations:* 200082.

*Optimum estimate found:*

*Function value:* 2860.00

*Estimated optimal solution vector (the components  $x_1$  to  $x_{50}$  are listed sequentially, by rows):*

-0.582359E+00	-0.480671E+00	-0.323575E+00	-0.856682E+00	-0.552137E+00
0.556333E-01	-0.782664E+00	-0.312315E-01	0.131451E+01	-0.182171E+01
-0.164235E+01	-0.105945E+00	-0.167769E+01	0.116252E+01	-0.617902E+00
-0.150214E+01	0.282612E+01	-0.217902E+00	-0.237475E+00	-0.582565E+00
0.288644E+00	0.221470E+01	-0.549966E+00	-0.254997E+01	-0.818971E+00
-0.375484E+00	-0.173881E+00	-0.199780E+01	-0.797261E+00	0.185765E+01
-0.477154E+00	-0.546158E+00	-0.116627E+01	-0.702672E+00	-0.117769E+01
-0.129399E+01	0.262505E+01	-0.457047E+00	-0.123747E+01	0.285765E+01
-0.118965E+01	0.133427E+01	0.247341E+01	-0.669539E+00	0.306146E+01
-0.917368E+00	-0.853239E+00	-0.137822E+01	-0.797261E+00	-0.160541E+01

Although this vector is, obviously, not a very precise approximation of the optimum—considering the initial large search interval—it is not too far

from it. (Increasing  $\max_g$ , improved global phase optimum estimates can be provided.) The subsequent local search, automatically launched from this point essentially finds the global optimum, as shown by the results below. (Note that, in fact, the local search phase was automatically terminated by LGO—in the absence of appreciable improvement of the objective function value—before the preset maximal number of steps would have been attained.)

### Local Search Phase

*Number of additional function evaluations:* 50262.

*Estimated optimum value:* 0.235088E-04.

*Estimated optimal solution vector (the components  $x(1)$  to  $x(50)$  are listed sequentially, by rows):*

0.169440E-03	0.162151E-03	-0.272220E-03	-0.115536E-03	0.525944E-03
0.355519E-03	0.460719E-03	0.303982E-03	-0.247225E-03	0.193031E-04
0.138270E-03	0.138394E-04	-0.491507E-04	0.161346E-03	0.834514E-04
0.256642E-03	0.895554E-04	0.767251E-04	-0.388216E-04	-0.397363E-04
-0.137227E-04	-0.137235E-03	-0.415906E-04	0.989787E-04	-0.825170E-04
-0.384140E-04	-0.253712E-03	0.181291E-04	-0.158941E-03	0.935380E-04
-0.204893E-03	0.757348E-04	0.123985E-03	-0.754476E-04	0.155654E-03
0.548079E-05	0.286140E-03	0.866373E-04	-0.107684E-03	0.120136E-03
0.924189E-04	0.176875E-04	0.365546E-04	0.183546E-03	0.125534E-03
0.965736E-04	0.410046E-04	-0.621115E-04	-0.803805E-04	-0.169211E-03

Considering the fact that the LGO solver does not rely on gradient information, the solution found is considered as an acceptable approximation of the zero vector.

The total computational effort—in terms of function evaluations—was 250344. According to the built-in PC timer, the described LGO test run was started at 12:28:35.10, and terminated at 12:56:42.79. The total runtime, hence, was about 28 min (on a PS/2 Intel 386&387DX, 8 Mbyte RAM PC, in a Lahey Fortran 77 runtime environment.) Note finally that this example was ‘not too difficult’ for LGO, but the global search phase was essential. To illustrate this point, note that launching a local search phase from the best solution found among 100 uniformly generated random sample points leads to a suboptimal solution in some 44,650 additional steps, when the local search is automatically terminated. (The corresponding objective function value equals 35.04.)

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5654E-03  
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### Example 2

In the second example, the objective function  $f$  is defined as follows.

$$f(x) = f_1(x) + f_2(x) + f_3(x), \quad \text{in which} \quad (3.4.4)$$

$$f_1(x) = \sum_{i=1}^n ix_i^2$$

$$f_2(x) = \sum_{i=1}^n i \sin^2(x_{i-1} \sin x_i - x_i + \sin x_{i+1})$$

$$f_3(x) = \sum_{i=1}^n i \ln(1 + i(x_{i-1}^2 - 2x_i + 3x_{i+1} - \cos x_i + 1)^2).$$

Again, by definition, in (3.4.4),  $x_0 = x_n$  and  $x_{n+1} = x_1$ . (The unique global minimum of (3.4.4) is the zero vector.)

Similar observations to those in connection with function (3.4.2) can be made. We have again the—rather badly scaled—quadratic function  $f_1$ , to which badly scaled noise terms are added this time. Although the individual terms in functions  $f_2$  and  $f_3$  can be relatively small, the  $i$ th terms are multiplied by the same factor  $i$ , as in  $f_1$ . Consequently, the relative ‘noise effect’ referred to can become quite substantial, especially for certain vectors  $x$  in the neighbourhood of the optimum. In summary, we have a similar test problem to that of Example 1, but the noise terms are probably somewhat more ‘tricky’. In the present test example, we choose again  $n = 50$ ; the components of the lower and upper bound vectors  $a$  and  $b$  are also given by (3.4.3), as in Example 1.

To minimize function (3.4.4) on  $[a, b]$  of (3.4.3) by the LGO program system, the maximal number of global and local phase search steps is chosen now as  $\max_g = 10^6$  and  $\max_l = 10^5$ , respectively. Although there are other built-in termination parameters, in the test example these values serve again to control the execution of LGO.

The results of the optimization run are summarized below; for additional related comments, recall the discussion of Example 1.

The value of the objective function (3.4.4) at the lower and the upper bound vectors equals  $f_a = 51386.43$ , and  $f_b = 37781.05$ —implying again a quite significant overall Lipschitz constant value.

### Global Search Phase

*Number of function evaluations:* 1000405.

*Optimum estimate found:*

*Function value:* 11021.52

*Estimated optimal solution vector (the components x(1) to x(50) are listed sequentially, by rows):*

-0.872199E+00	-0.261361E+00	0.958211E+00	0.355886E+00	0.977738E+00
0.255926E+01	0.195261E+01	0.629367E-01	-0.221148E+01	-0.304696E+00
-0.174208E+01	-0.188451E+00	-0.174932E+01	0.109997E+01	-0.698596E+00
-0.159280E+01	0.274633E+01	-0.298595E+00	-0.300035E+00	-0.691365E+00
0.146298E+00	0.215939E+01	-0.633379E+00	-0.263338E+01	-0.944997E+00
-0.523271E+00	-0.253667E+00	-0.207396E+01	-0.850754E+00	0.175792E+01
-0.526114E+00	-0.637731E+00	-0.126237E+01	-0.816005E+00	-0.124932E+01
-0.137831E+01	0.249993E+01	-0.501474E+00	-0.130003E+01	0.275792E+01
-0.125946E+01	0.126083E+01	0.236371E+01	-0.734819E+00	0.295356E+01
-0.975394E+00	-0.905826E+00	-0.147252E+01	-0.850754E+00	-0.166525E+01

One should recall that the objective function value is the sum of 150 terms, several of them being highly ‘amplified’. This explains the large objective function value, found in a relatively close vicinity of the global optimum. Again, the subsequent local search phase automatically refines this solution.

### Local Search Phase

*Number of additional function evaluations:* 64776.

*Estimated optimum value:* 0.116325E-02.

*Estimated optimal solution vector (the components x(1) to x(50) are listed sequentially, by rows):*

0.246135E-04	-0.496429E-02	-0.256523E-02	-0.948861E-03	0.523864E-04
0.546945E-03	0.743775E-03	0.942086E-03	0.904422E-03	0.825253E-03
0.707861E-03	0.607685E-03	0.559501E-03	0.493742E-03	0.403791E-03
0.312093E-03	0.200017E-03	0.940176E-04	0.361621E-04	-0.168630E-04
-0.556142E-04	-0.722397E-04	-0.671281E-04	-0.372672E-04	-0.188569E-04
-0.130694E-04	-0.354038E-04	-0.456414E-04	-0.669419E-04	-0.683881E-04
-0.887829E-04	-0.146445E-03	-0.142459E-03	-0.137900E-03	-0.103197E-03
-0.680875E-04	-0.669518E-04	-0.721837E-04	-0.702192E-04	-0.619646E-04
-0.476193E-04	-0.441888E-04	-0.424293E-04	-0.609721E-04	-0.608845E-04
-0.573608E-04	-0.468054E-04	-0.331098E-04	-0.107399E-04	0.107129E-04

Again—since LGO is a derivative-free solver—the accuracy obtained seems to be acceptable.

The total number of objective function evaluations in Example 2 is 1065181. The LGO run was started at 09:25:01.22, and was automatically terminated at 13:37:22.03—the runtime is over four hours(!). This can be said to be quite significant, but problem (3.4.4) indeed is a bit ‘tricky’, and—at least in the field of numerical global optimization—the number of variables is not too small. On faster personal computers, workstations, mainframes, supercomputers, parallel computer architectures, etc. (available today), the runtime could be reduced by, say, a factor of 10-500. The essential numerical message, however, is that—for all speed computers of today and tomorrow are able to provide—it is easy to find (test and real) global optimization problems which would immediately call for more power.

A variety of further numerical examples, related to diverse applications, will be discussed in Part 4. Since in many of these applications—and also in other areas of multiextremal optimization—uncertainties and statistical fluctuations will play a significant role, in the remainder of Part 3 stochastic decision models and solution techniques will be discussed. Within this framework, we shall discuss a general class of stochastic solution strategies that can be applied to solve—deterministic or stochastic—global optimization problems, under mild analytical assumptions. This will provide another generic methodology for continuous and Lipschitzian global optimization (and, in fact, will be applied in relation to several applications in Part 4).

) are listed

.977738E+00  
.304696E+00  
.698596E+00  
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.944997E+00  
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08845E-04  
07129E-04

Before turning to an illustrative numerical performance study, let us present an example of solving a three-variable test problem. This problem consists of finding a vector  $\mathbf{x} = (x_1, x_2, x_3)$  on the interval

$$D = \{1.0 \leq x_1 \leq 2.5; 0.2 \leq x_2 \leq 2.0; 0.1 \leq x_3 \leq 3.0\} \quad (4.1.11)$$

which (approximately) solves the following system of equations:

$$f_1(\mathbf{x}) = 0.1x_1 + \cos(2x_2) + 0.09240 = 0 \quad (4.1.12)$$

$$f_2(\mathbf{x}) = \sin(10x_1/3) + \ln(2x_2) - 2.52x_3 + \sin(3x_3) + 0.08805 = 0$$

$$f_3(\mathbf{x}) = 2(x_1 - 0.75)^2 + \sin(16\pi x_2 - \pi/2) - 3.26815 = 0.$$

Note that (4.1.12) has a number of ‘locally best’ generalized solutions on  $D$  with significant nonzero residuals: thus, the application of some standard (local) solution method would typically lead to one of these. The approximate global solution is

$$x_1^* \approx 1.85210, \quad x_2^* \approx 0.92605, \quad x_3^* \approx 0.61737, \quad f(\mathbf{x}^*) = \sum_{j=1}^3 |f_j(\mathbf{x}^*)| < 10^{-5}.$$

Solving the optimization problem, induced by (4.1.11)–(4.1.12), in the form

$$\min \left\{ \sum_{j=1}^m |f_j(\mathbf{x})| : \mathbf{x} \in D \right\},$$

and applying the diagonal extension of Piyavskii’s algorithm, one can follow the optimum estimates produced by the outlined algorithm in its global search phase: several steps are shown in Table 4.1.1. (The global search phase was restricted to 150 steps in this illustrative numerical example.)

The best approximation of the solution, found in step 96, is fairly close to  $\mathbf{x}^*$  but, because of ‘abrupt’ changes of the objective function, the corresponding residual is still significant. The local refinement phase needs an additional 180 steps (function and gradient evaluations) to reach the optimal solution from its approximation found in step 96: this indicates the relative difficulty of problem (4.1.11)–(4.1.12).

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**Table 4.1.1**  
**Solution of problem (4.1.11)–(4.1.12):**  
**several global search phase approximations**

(4.1.11)	No. of global search phase steps	Approximate solution found	Function value
14	(1.8465, 1.2159, 0.7363)	1.4030	
29	(1.7500, 0.7079, 0.6637)	1.9309	
34	(1.9044, 1.6886, 0.7797)	1.2089	
64	(1.7500, 1.2159, 0.6478)	1.7735	
83	(1.9044, 1.2159, 0.6637)	1.2156	
96	(1.7500, 0.9251, 0.6478)	0.8698	
148	(2.2022, 1.6079, 0.9455)	1.0251	

#### 4.1.4 Test Results on Randomly Generated System of Equations

In order to obtain a more realistic and detailed assessment concerning robustness and efficiency of the global optimization approach outlined, two classes of pseudo-random test problems are chosen for further analysis. Randomized problem classes are advantageous when compared to individually selected problems, for the following reasons:

- they make possible a statistically sound evaluation of the method in question (with respect to the problem-class studied) under mild and general probabilistic assumptions;
- they are easy to generate sequentially;
- they are unambiguously reproducible, thus facilitating more objective evaluation and comparison of different methods.

For instance, random two-variate test problems were considered in Strongin (1978), for comparing several global optimization algorithms.

#### Trigonometric Systems of Equations

In the following set of numerical experiments, our objective is to find the solution of the system of equations

$$\begin{aligned} f_i(\mathbf{x}) &= \sum_{j=1}^n \{ A_{ij} \sin^2 \{ B_{ij} (\mathbf{x}_j - \mathbf{x}_j^*) \} + C_{ij} \sin^2 \{ D_{ij} (\mathbf{x}_j - \mathbf{x}_j^*) \} \} \\ &\quad + (\mathbf{x}_i - \mathbf{x}_i^*)^2 = 0, \quad i = 1, \dots, n, \end{aligned} \quad (4.1.13)$$

$$\mathbf{x} \in D = \{ \mathbf{x} = (\mathbf{x}_1, \dots, \mathbf{x}_n) : -\pi \leq \mathbf{x}_j \leq \pi, j = 1, \dots, n \}. \quad (4.1.14)$$

The parameters in (4.1.13) follow randomized generation rules as described below:

- the components of the solution vector,  $\mathbf{x}_j^*, j = 1, \dots, n$ , are independent identically distributed (i.i.d.), uniform random variables on the interval  $[-\pi, \pi]$ ;
- the multipliers  $A_{ij}, B_{ij}, C_{ij}, D_{ij}$  ( $i, j = 1, \dots, n$ ) are i.i.d. uniform random variables on the interval  $[1, 6]$ ;
- these parameters are generated sequentially in the following order:  $\mathbf{x}^*$  componentwise, the matrices  $A, B, C, D$  row by row;
- for generating these values, the simple pseudo-random number generator

$$\begin{aligned} r_1 &= \sin(0.86), \quad r_2 = \sin(0.23), \quad r_{k+2} = r_k + r_{k+1} \pmod{1}, \\ (k &= 1, 2, 3, \dots) \end{aligned}$$

is applied. (This random number generator is not very sophisticated, but it is very easy to (re)produce, and is adequate for the purposes of the present numerical example.)

For illustration, we shall cite the first pseudo-random problem generated:

$$\begin{aligned} n &= 2, \quad \mathbf{x}_1^* = 3.052498, \quad \mathbf{x}_2^* = -1.798262; \\ A = [A_{ij}] &= \begin{bmatrix} 1.998089 & 3.067078 \\ 4.065167 & 1.132245 \end{bmatrix}; \quad B = [B_{ij}] = \begin{bmatrix} 4.197412 & 4.329657 \\ 2.527069 & 5.856725 \end{bmatrix}; \\ C = [C_{ij}] &= \begin{bmatrix} 2.384794 & 2.240519 \\ 3.624313 & 4.864832 \end{bmatrix}; \quad D = [D_{ij}] = \begin{bmatrix} 2.489146 & 1.353978 \\ 2.843124 & 3.197102 \end{bmatrix}. \end{aligned}$$

A few comments related to the problem class (4.1.13)–(4.1.14) are in order. Besides the unique global optimum  $\mathbf{x}^*$ , several locally best ‘solutions’

$x_j^*)\}$ 

(4.1.13)

(4.1.14)

rules as de-

dependent  
the interval

d. uniform

$$f(x) = 5 \sin^2\{2(x-1)\} + 3 \sin^2\{4(x-1)\} + 0.2(x-1)^2$$

$$-\pi \leq x \leq \pi, \quad (x^* = 1, f(x^*) = 0)$$

; order:  $x^*$ 

; generator

d 1),

..)

histicated,  
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generated:

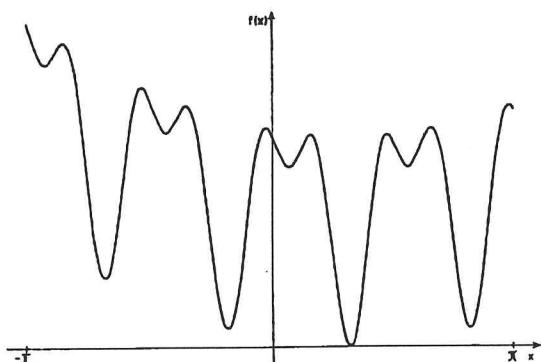
329657  
856725]353978  
197102]4) are in  
olutions'

Figure 4.1.1

A univariate trigonometric equation  
with several local ‘solutions’ (minima)

exist with nonzero residuals. The actual number of these ‘pseudo-solutions’ strongly depends on the random realization of problem parameters. Note also that the fluctuating trigonometric terms may cause significant ‘jumps’ of the derived objective function

$$\sum_{i=1}^n |f_i(x)|, \quad x \in D. \quad (4.1.15)$$

For illustration, see Fig. 4.1.1, which shows a function closely related to the class of functions (4.1.13). (For a more pronounced graphical effect of the trigonometric terms, the quadratic term is ‘scaled down.’)

It is obvious that only the additional quadratic terms  $(x_i - x_i^*)^2$  provide an ‘explicit’ orientation towards finding the global solution in each function  $f_i$ ,  $i = 1, \dots, n$ .

The structure of (4.1.13)–(4.1.14) would not permit the application of a standard equation solver, unless a close local estimate of  $x^*$  can be provided. For example, several locally best generalized (approximate) solutions of the

equation

$$5 \sin^2\{2(x - 1)\} + 3 \sin^2\{4(x - 1)\} + 0.2(x - 1)^2 = 0, \quad -\pi \leq x \leq \pi$$

are (see Fig. 4.1.1):

$$x_1 = -2.898 \quad f_1 = 8.062; \quad x_2 = -0.566 \quad f_2 = 0.492;$$

$$x_3 = 1.780 \quad f_3 = 5.123; \quad x_4 = 2.566 \quad f_4 = 0.492;$$

while, obviously,  $x^* = 1$  and  $f(x^*) = 0$ .

A number of instances of the problem-class (4.1.13)–(4.1.14) were solved by the global optimization procedure under different algorithm specifications. These specifications are related primarily to the stopping criteria applied and the method by which the Lipschitz constant of the objective function (4.1.15) is (over)estimated.

Recall that the algorithm outlined earlier has two termination criteria, as follows:

- The approximate solution found in the global search phase is ‘acceptable’ (as expressed by parameter  $\alpha$ ). Note that this criterion is specific to the present problem-class, and is based on the assumption that we are interested only in the (by supposition, existing) solution. Although this reflects a somewhat ‘ideal’ problem setting, for testing purposes and by its practical relevance its use is justified.
- The subinterval selected for further partition is ‘sufficiently small’ (as expressed by parameter  $\delta$ ). (This criterion is based on the convergence results discussed in Part 2.)

Let us recall here (Chapter 3.2) that the estimation of the Lipschitz constant is probably the most crucial numerical issue in Lipschitzian optimization. In the present numerical study, two simple approximation methods are used. The first (trivial but often used) approach is to provide an overall estimate which might be a grossly exaggerated or a false value, while the second is an approximation on the basis of the sample points taken from the adaptively generated subintervals and the corresponding function values. The first of these approaches will be referred to as the ‘overall’ estimation method, while the second is called the ‘adaptive’ estimation technique.

In the first sequence of trial runs, 100 two-variate test problems were generated and solved with tolerances  $\alpha = 1$ ,  $\delta = 0.2$ . In addition, the

overall Lipschitz-constant estimate  $L = 20$  was used: note that this might be an underestimate of the (random) problem-specific value  $L$ . In 93 cases, the system of equations was solved (up to seven digits of accuracy in the argument  $x^*$ ); in the remaining seven cases only ‘good’ local minima were found. Denoting the empirical mean and standard deviation of the number of global and local search phase steps respectively by  $E(n_{glob})$ ,  $D(n_{glob})$  and by  $E(n_{loc})$ , by  $D(n_{loc})$ , the following (approximate) run characteristics were obtained:

$$E(n_{glob}) = 489, \quad D(n_{glob}) = 290 \quad \text{and} \quad E(n_{loc}) = 12, \quad D(n_{loc}) = 5.4.$$

Recalling that in the global search phase steps only the function values are sampled, the above statistical characteristics seem to be reasonable. Note that, as reflected by the small number of local terminating steps, the global search delivered a truly close approximation of the (global or local) solution  $x^*$ .

In the second set of runs, 50 two-variate test problems were generated and solved using the parameters  $\alpha = 0.5$ ,  $\delta = 0.0001$ , and  $L = 10$ . The set value of  $\delta$  implies that the second numerical stopping criterion is practically excluded. Moreover, the above value of  $L$  is often smaller than the minimal true value for the actually realized problem. The results clearly showed the negative consequences of the stated settings. Only 38 problems were solved exactly, and the run characteristics also became less favourable:

$$E(n_{glob}) = 604, \quad D(n_{glob}) = 664 \quad \text{and} \quad E(n_{loc}) = 15, \quad D(n_{loc}) = 9.7.$$

A closer look at the individual runs showed that although in some cases the solution was produced in a few (50–100) algorithm steps, a crude underestimate of  $L$  could cause some local deviations and resulted in long execution times.

On the basis of this observation, a third set of experiments was accomplished with the following parameters:

$$\alpha = 1, \quad \delta = 0.6, \quad L = 20\sqrt{2}, \quad maxfct = 200, 300, 500, 2000,$$

where  $maxfct$  denotes the maximal number of global search phase function evaluations introduced to model the effect of interrupting the ‘long’ runs.

**Table 4.1.2**  
**Random two-variable trigonometric equation systems:**  
**Summary of test results**

<i>maxfct</i>	Number of successful solutions	<i>E(nglob)</i>	<i>D(nglob)</i>	<i>E(nloc)</i>	<i>D(nloc)</i>
200	32	189	35	17	7.1
300	36	263	71	17	7.2
500	44	335	177	15	6.5
2000	50	710	486	11	2.8

Solving 50 randomly generated problems in each case, the results are summarized in Table 4.1.2.

As Table 4.1.2 indicates, the increase of *maxfct* gradually leads to ‘perfect’ performance, but also to the increase of average global search effort and its variance (without much effect with respect to the local search characteristics). It is notable that relatively few (200) global search steps are already sufficient to solve some two-thirds of the problems.

Closing the illustrative study of this function-class, note that the successful solution of 50 three-variate problems (all solved using the parameters  $\alpha = 1$ ,  $\delta = 0.6$ ,  $L = 50$ ) resulted in the following run characteristic:

$$E(\text{nglob}) = 1764, \quad D(\text{nglob}) = 384 \quad \text{and} \quad E(\text{nloc}) = 21, \quad D(\text{nloc}) = 13.$$

The simple run statistics presented highlight the expected difficulty of solving random instances of the problem class (4.1.13)–(4.1.14).

### Shekel-Type Systems of Equations

The second problem class, discussed here, has its origin in the early global optimization literature, see, for instance, Dixon and Szegö (1978). The problem is to find the solution of the system of equations

$$f_i(\mathbf{x}) = (\mathbf{x}_i - \mathbf{x}_i^*)^2 - \sum_{j=3(i-1)+1}^{3i} \frac{1}{\|\mathbf{x} - \mathbf{d}_j\|^2 + c_j} + k_i = 0, \quad i = 1, \dots, n, \quad (4.1.16)$$

( $\|\cdot\|$  is the Euclidean norm) on the region

$$D = \{\mathbf{x} = (x_1, \dots, x_n) : 0 \leq x_j \leq 10, j = 1, \dots, n\}. \quad (4.1.17)$$

The functions (4.1.16) are generated sequentially according to the following rules (applying again the simple pseudo-random number generator described earlier):

- the components of the solution vector  $x^*$  are i.i.d. uniform random variables (u.r.v.'s) on the interval [0.5, 9.5];
- the term  $c_1$  is a u.r.v. on [0.1, 1];  $c_2 = c_1 + r_2$ ;  $c_j = c_2 + r_j$ ,  $j = 3, \dots, 3n$ , where  $r_2, \dots, r_{3n}$  are i.i.d. u.r.v.'s on [0, 1];
- the  $n$ -vector  $d_1$  is identical to  $x^*$ , the other vectors  $d_2, \dots, d_{3n}$  have i.i.d. components, all of them being u.r.v.'s on [0, 10];
- the constants  $k_i$  are adjusted finally, in order to satisfy the equations (4.1.16) for  $x = x^*$ .

Note that the above generating rules assure that  $x \approx x^*$  is the unique globally optimal solution; besides that solution, each equation in (4.1.16) has three 'locally best' (generalized) solutions. Consequently, the optimization problem derived, say, in the  $l_2$ -norm form

$$\min\{f(x) : x \in D\}, \quad f(x) = \sum_{i=1}^n f_i^2(x), \quad (4.1.18)$$

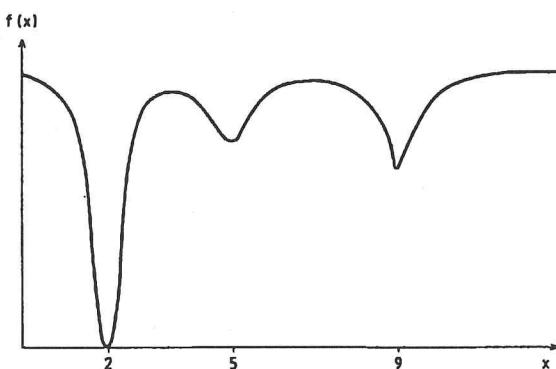
has  $m = 3n$  local generalized solutions. Note that the Shekel-type functions (namely, the sum term in the definition of  $f_i$ ) are characterized by a rather 'flat plateau' which is modified by the 'valleys' corresponding to local optima (see Fig. 4.1.2). The additional terms  $(x_i - x_i^*)^2$  modify the somewhat 'flat' character of  $f$ , and thus have an 'orientating effect' towards the globally optimal solution.

For illustration, the parameters of the first univariate test problem generated by the above rules are as follows:

$$x_i^* = 9.500000; \quad c_1 = 0.213798; \quad c_2 = 0.463416; \quad c_3 = 0.876831;$$

$$d_1^* = 9.500000; \quad d_2 = 6.130334; \quad d_3 = 0.264490; \quad k_1 = 4.773540.$$

Similarly to the previously described test runs, the stopping criteria, parameterized by  $\alpha$  (now the bound of the summarized squared errors) and  $\delta$  (the bound of the  $l_1$ -norm of the subinterval selected for further partition), were used. In this example, however, interval-specific Lipschitz constants were estimated on the basis of those search points which are generated on the



$$f(x) = -\frac{1}{(x-2)^2 + 0.1} - \frac{1}{(x-5)^2 + 0.4} - \frac{1}{(x-9)^2 + 0.3} + 10.126667; \\ 0 \leq x \leq 10.$$

**Figure 4.1.2**  
**A Shekel-type univariate function**

subinterval in question (namely, its central point, a quadratic interpolation point, another linear interpolation point, and the vertices of the main diagonal), before its bisection is done. Note that—in accordance with the related brief discussion in Chapter 3.1—this simple method was expected to have numerical advantages when compared to the (usually rather crude) ‘overall’ Lipschitz-constant estimation approach applied in solving the trigonometric test problems (4.1.13)–(4.1.14).

Five hundred test runs were accomplished, 100 randomly generated problems for  $n = 1, \dots, 5$ . To decrease somewhat the computational burden of this experiment—and to see the ‘success rate’ of the global search phase—only the global search phase was carried out in each case. Therefore the solution was considered ‘successful’ in the global sense, if at least one of the following termination criteria was satisfied:

- the total squared error of the equations was less than  $\alpha = 0.25n$ , or
- when terminating a run by the stopping rule  $\delta = 0.01n$ , the  $l_1$ -distance between the global phase approximate solution and  $x^*$  was less than  $0.25n$ .

**Table 4.1.3**  
**Shekel-type systems of equations:**  
**Summary of test results**

Number of variables	Number of successful solutions	Expected number of global phase function evaluations	Standard deviation
1	100	11	13
2	98	137	203
3	100	522	407
4	100	2138	820
5	99	10471	6499

Let us note that, as several detailed test results indicated, in most cases these criteria yielded approximate solutions within the componentwise 0.01–0.05 neighbourhood of  $\mathbf{x}^*$ . Even the few ‘bad’ results had only at most 0.3–0.4 componentwise errors. For comparison, note that the trivial uniform grid search applied on the region  $[0, 10]^n$  would need about  $20^n$  function calls for meeting the second criterion of ‘successful search’. The results of the test runs are summarized in Table 4.1.3.

As noted earlier, even the (3 in 500) approximate solutions were situated in a close neighbourhood of  $\mathbf{x}^*$ , although somewhat missing the  $\alpha$  or  $\delta$  threshold. The runtime printouts indicated that some test problems were quite difficult: the objective function changed in an extremely abrupt manner close to  $\mathbf{x}^*$ . This circumstance explains the large number of steps in some cases. For example, one of the five-variate problems needed more than 22,000 function evaluations, though in most cases some 1,500 steps were sufficient and a number of problems were solved in less than 200 steps.

Without attempting a (probably not sufficiently sound) statistical analysis of these results, it is instructive to plot the expected number  $E(n_{\text{glob}})$  of global phase function evaluations, on logarithmic scale, against  $n$ , the number of test problem variables (see Fig. 4.1.3). As this figure suggests, the number of function evaluations increases by a factor of about four (starting this tendency from  $n = 2$ : the univariate problems are ‘too easy’). Plots similar to Fig. 4.1.3 make it possible to estimate the necessary effort to solve problems from a given class by applying, say, the normal distribution approximation induced by the central limit theorem (see, for example, Feller, 1971).

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