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# GALAHAD

# LMS

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USER DOCUMENTATION

GALAHAD Optimization Library version 3.0

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## 1 SUMMARY

Given a sequence of vectors  $\{\mathbf{s}_k\}$  and  $\{\mathbf{y}_k\}$  and scale factors  $\delta_k$ , **obtain the product of a limited-memory secant approximation  $H_k$  (or its inverse) with a given vector**, using one of a variety of well-established formulae.

**ATTRIBUTES — Versions:** GALAHAD\_LMS\_single, GALAHAD\_LMS\_double. **Uses:** GALAHAD\_CLOCK, GALAHAD\_SYMBOLS, GALAHAD\_SPACE, GALAHAD\_LAPACK\_interface, GALAHAD\_BLAS\_interface, GALAHAD\_SPECFILE. **Date:** July 2014. **Origin:** N. I. M. Gould, Rutherford Appleton Laboratory. **Language:** Fortran 95 + TR 15581 or Fortran 2003.

## 2 HOW TO USE THE PACKAGE

Access to the package requires a USE statement such as

*Single precision version*

```
USE GALAHAD_LMS_single
```

*Double precision version*

```
USE GALAHAD_LMS_double
```

If it is required to use both modules at the same time, the derived types `SMT_type`, `LMS_time_type`, `LMS_control_type`, `LMS_inform_type` and `LMS_data_type` (§2.1) and the subroutines `LMS_initialize`, `LMS_setup`, `LMS_form`, `LMS_form_shift`, `LMS_apply`, `LMS_terminate`, (§2.2) and `LMS_read_specfile` (§2.4) must be renamed on one of the USE statements.

### 2.1 The derived data types

Four derived data types are accessible from the package.

#### 2.1.1 The derived data type for holding control parameters

The derived data type `LMS_control_type` is used to hold controlling data. Default values may be obtained by calling `LMS_initialize` (see §2.2.1), while components may also be changed by calling `GALAHAD_LMS_read_spec` (see §2.4.1). The components of `LMS_control_type` are:

`error` is a scalar variable of type default `INTEGER`, that holds the stream number for error messages. Printing of error messages in `LMS_setup`, `LMS_apply` and `LMS_terminate` is suppressed if `error`  $\leq 0$ . The default is `error` = 6.

`out` is a scalar variable of type default `INTEGER`, that holds the stream number for informational messages. Printing of informational messages in `LMS_setup`, `LMS_apply` is suppressed if `out`  $< 0$ . The default is `out` = 6.

`print_level` is a scalar variable of type default `INTEGER`, that is used to control the amount of informational output which is required. No informational output will occur if `print_level`  $\leq 0$ . If `print_level` = 1, a single line of output will be produced for each level of the process. If `print_level`  $\geq 2$ , this output will be increased to provide significant detail of the factorization. The default is `print_level` = 0.

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`memory_length` is a scalar variable of type default `INTEGER`, that is used to specify the maximum number of vectors  $\{\mathbf{s}_k\}$  and  $\{\mathbf{y}_k\}$  that will be used when building the secant approximation. Any non-positive value will be interpreted as 1. The default is `memory_length = 10`.

`method` is a scalar variable of type default `INTEGER`, that is used to specify the limited-memory formula that will be applied. Possible values are

- 1 . A limited-memory BFGS formula will be applied.
- 2 . A limited-memory symmetric rank-one formula will be applied.
- 3 . The inverse of the limited-memory BFGS formula will be applied.
- 4 . The inverse of the shifted limited-memory BFGS formula will be applied. This should be used instead of `%method = 3` whenever a shift is planned.

Any value outside this range will be interpreted as 1. The default is `method = 1`.

`any_method` is a scalar variable of type default `LOGICAL`, that must be set `.TRUE.` if more than one method (see `%method` above) is to be used and `.FALSE.` otherwise. The package will require more storage and may run slower if `any_method` is `.TRUE.`. The default is `any_method = .FALSE.`

`space_critical` is a scalar variable of type default `LOGICAL`, that must be set `.TRUE.` if space is critical when allocating arrays and `.FALSE.` otherwise. The package may run faster if `space_critical` is `.FALSE.` but at the possible expense of a larger storage requirement. The default is `space_critical = .FALSE.`

`deallocate_error_fatal` is a scalar variable of type default `LOGICAL`, that must be set `.TRUE.` if the user wishes to terminate execution if a deallocation fails, and `.FALSE.` if an attempt to continue will be made. The default is `deallocate_error_fatal = .FALSE.`

`prefix` is a scalar variable of type default `CHARACTER` and length 30, that may be used to provide a user-selected character string to preface every line of printed output. Specifically, each line of output will be prefaced by the string `prefix(2:LEN(TRIM(prefix))-1)`, thus ignoring the first and last non-null components of the supplied string. If the user does not want to preface lines by such a string, they may use the default `prefix = ""`.

### 2.1.2 The derived data type for holding timing information

The derived data type `LMS_time_type` is used to hold elapsed CPU and system clock times for the various parts of the calculation. The components of `LMS_time_type` are:

`total` is a scalar variable of type default `REAL` (double precision in `GALAHAD_LMS_double`), that gives the total CPU time spent in the package.

`setup` is a scalar variable of type default `REAL` (double precision in `GALAHAD_LMS_double`), that gives the CPU time spent setting up the data structures to represent the limited-memory matrix.

`form` is a scalar variable of type default `REAL` (double precision in `GALAHAD_LMS_double`), that gives the CPU time spent forming and updating the limited-memory matrix as new data arrives.

`apply` is a scalar variable of type default `REAL` (double precision in `GALAHAD_LMS_double`), that gives the CPU time spent applying the matrix to given vectors.

`clock_total` is a scalar variable of type default `REAL` (double precision in `GALAHAD_LMS_double`), that gives the total elapsed system clock time spent in the package.

`clock_setup` is a scalar variable of type default `REAL` (double precision in `GALAHAD_LMS_double`), that gives the elapsed system clock time spent setting up the data structures to represent the limited-memory matrix.

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`clock_form` is a scalar variable of type default `REAL` (double precision in `GALAHAD_LMS_double`), that gives the elapsed system clock time spent forming and updating the limited-memory matrix as new data arrives.

`clock_apply` is a scalar variable of type default `REAL` (double precision in `GALAHAD_LMS_double`), that gives the elapsed system clock time spent applying the matrix to given vectors. factor **R**.

### 2.1.3 The derived data type for holding informational parameters

The derived data type `LMS_inform_type` is used to hold parameters that give information about the progress and needs of the algorithm. The components of `LMS_inform_type` are:

`status` is a scalar variable of type default `INTEGER`, that gives the exit status of the algorithm. See §2.3 for details.

`alloc_status` is a scalar variable of type default `INTEGER`, that gives the status of the last attempted array allocation or deallocation. This will be 0 if `status = 0`.

`bad_alloc` is a scalar variable of type default `CHARACTER` and length 80, that gives the name of the last internal array for which there were allocation or deallocation errors. This will be the null string if `status = 0`.

`length` is a scalar variable of type default `INTEGER`, that gives the number of pairs  $\{s_k, y_k\}$  currently used to represent the limited-memory matrix

`updates_skipped` is a scalar variable of type default `LOGICAL`, that will be `.TRUE.` if one or more of the current pairs  $\{s_k, y_k\}$  has been ignored for stability reasons when building the current limited-memory matrix, and `.FALSE.` otherwise.

`time` is a scalar variable of type `LMS_time_type` whose components are used to hold elapsed CPU and system clock times for the various parts of the calculation (see Section 2.1.2).

### 2.1.4 The derived data type for holding problem data

The derived data type `LMS_data_type` is used to hold all the data for the problem and the workspace arrays used to construct the multi-level incomplete factorization between calls of `LMS` procedures. This data should be preserved, untouched, from the initial call to `LMS_initialize` to the final call to `LMS_terminate`.

## 2.2 Argument lists and calling sequences

There are seven procedures for user calls (see §2.4 for further features):

1. The subroutine `LMS_initialize` is used to set default values, and initialize private data, before solving one or more problems with the same sparsity and bound structure.
2. The subroutine `LMS_setup` is called to set up the data structures needed to represent the limited-memory matrix  $\mathbf{H}_k$  or its inverse.
3. The subroutine `LMS_form` is called to form the limited-memory matrix  $\mathbf{H}_k$  or its inverse as new data  $(s_k, y_k, \delta_k)$  arrives. The matrix  $\mathbf{H}_k + \lambda_k \mathbf{I}$  or its inverse for a specified shift  $\lambda_k$  may be formed instead.
4. The subroutine `LMS_form_shift` is called to update the inverse of the limited-memory matrix  $\mathbf{H}_k + \lambda_k \mathbf{I}$  when a new shift  $\lambda_k$  is required.
5. The subroutine `LMS_change_method` is called to build the limited-memory matrices  $\mathbf{H}_k, \mathbf{H}_k + \lambda_k \mathbf{I}$  or their inverse for a new method from the current data.

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6. The subroutine `LMS_apply` is called to form the product  $\mathbf{u} = \mathbf{H}_k \mathbf{v}$ ,  $\mathbf{u} = (\mathbf{H}_k + \lambda_k \mathbf{I}) \mathbf{v}$ ,  $\mathbf{u} = \mathbf{H}_k^{-1} \mathbf{v}$  or  $\mathbf{u} = (\mathbf{H}_k + \lambda_k \mathbf{I})^{-1} \mathbf{v}$  for a given vector  $\mathbf{v}$ .
7. The subroutine `LMS_terminate` is provided to allow the user to automatically deallocate array components of the private data, allocated by `LMS_setup` at the end of the solution process.

We use square brackets [ ] to indicate OPTIONAL arguments.

### 2.2.1 The initialization subroutine

Default values are provided as follows:

```
CALL LMS_initialize( data, control, inform )
```

`data` is a scalar INTENT(INOUT) argument of type `LMS_data_type` (see §2.1.4). It is used to hold data about the problem being solved.

`control` is a scalar INTENT(OUT) argument of type `LMS_control_type` (see §2.1.1). On exit, `control` contains default values for the components as described in §2.1.1. These values should only be changed after calling `LMS_initialize`.

`inform` is a scalar INTENT(OUT) argument of type `LMS_inform_type` (see Section 2.1.3). A successful call to `LMS_initialize` is indicated when the component `status` has the value 0. For other return values of `status`, see Section 2.3.

### 2.2.2 The subroutine for setting up the required data structures

The data structures needed to represent the limited-memory matrix  $\mathbf{H}_k$  or its inverse are set up as follows:

```
CALL LMS_setup( n, data, control, inform )
```

`n` is a scalar INTENT(IN) argument of type default INTEGER, that must be set to the dimension of the limited-memory matrix required. **Restriction:**  $n \geq 1$ .

`data` is a scalar INTENT(INOUT) argument of type `LMS_data_type` (see §2.1.4). It is used to hold data about the factors obtained. It must not have been altered by the user since the last call to `LMS_initialize`.

`control` is a scalar INTENT(IN) argument of type `LMS_control_type` (see §2.1.1). Default values may be assigned by calling `LMS_initialize` prior to the first call to `LMS_setup`.

`inform` is a scalar INTENT(OUT) argument of type `LMS_inform_type` (see §2.1.3). A successful call to `LMS_setup` is indicated when the component `status` has the value 0. For other return values of `status`, see §2.3.

### 2.2.3 The subroutine for updating the limited memory matrix

The required limited memory matrix is updated to accommodate the incoming triple  $(\mathbf{s}_k, \mathbf{y}_k, \delta_k)$  as follows:

```
CALL LMS_form( S, Y, delta, data, control, inform[, lambda] )
```

`S` is an INTENT(IN) rank-1 array of type REAL (double precision in `GALAHAD_LMS_double`) and length at least as large as the value `n` as set on input to `LMS_setup`, whose first `n` components must hold the incoming vector  $\mathbf{s}_k$ .

`Y` is an INTENT(IN) rank-1 array of type REAL (double precision in `GALAHAD_LMS_double`) and length at least as large as the value `n` as set on input to `LMS_setup`, whose first `n` components must hold the incoming vector  $\mathbf{y}_k$ . **Restriction:** the update will be skipped for limited-memory BFGS methods if the inner product  $\mathbf{s}_k^T \mathbf{y}_k \leq 0$ .

`delta` is an INTENT(IN) REAL (double precision in `GALAHAD_LMS_double`) scalar that must hold the value  $\delta_k$ . **Restriction:** the update will be skipped if  $\delta_k \leq 0$ .

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`data` is a scalar `INTENT(INOUT)` argument of type `LMS_data_type` (see §2.1.4). It is used to hold data about the factors obtained. It must not have been altered **by the user** since the last call to `LMS_setup`.

`control` is a scalar `INTENT(IN)` argument of type `LMS_control_type` (see §2.1.1). Default values may be assigned by calling `LMS_initialize` prior to the first call to `LMS_setup`.

`inform` is a scalar `INTENT(OUT)` argument of type `LMS_inform_type` (see §2.1.3). A successful call to `LMS_setup` is indicated when the component `status` has the value 0. For other return values of `status`, see §2.3.

`lambda` is an OPTIONAL, `INTENT(IN)` REAL (double precision in `GALAHAD_LMS_double`) scalar that if present will be used to specify the shift  $\lambda_k$  that is used by the limited memory methods defined by `control%method = 1, 2` or 4. **Restriction:** the update will be skipped if `lambda < 0` for these methods.

#### 2.2.4 The subroutine for shifting the limited-memory matrix

The required limited memory matrix is updated to accommodate the shift  $\lambda_k$  as follows—this call is mandatory when `control%method = 4` if  $\lambda_k$  was not set during the call to `LMS_form`:

```
CALL LMS_form_shift( lambda, data, control, inform )
```

`lambda` is an `INTENT(IN)` REAL (double precision in `GALAHAD_LMS_double`) scalar that must hold the value  $\lambda_k$ . **Restriction:** the update will be skipped if `lambda < 0` or if `control%method = 3`.

`data` is a scalar `INTENT(INOUT)` argument of type `LMS_data_type` (see §2.1.4). It is used to hold data about the factors obtained. It must not have been altered **by the user** since the last call to `LMS_form`.

`control` is a scalar `INTENT(IN)` argument of type `LMS_control_type` (see §2.1.1). Default values may be assigned by calling `LMS_initialize` prior to the first call to `LMS_setup`.

`inform` is a scalar `INTENT(OUT)` argument of type `LMS_inform_type` (see §2.1.3). A successful call to `LMS_setup` is indicated when the component `status` has the value 0. For other return values of `status`, see §2.3.

#### 2.2.5 The subroutine for changing the method defining the limited-memory matrix

The required limited memory matrix is updated to accommodate the shift  $\lambda_k$  as follows—this call is only permitted if `control%any_method = .TRUE.` was set when `LMS_setup` was originally called:

```
CALL LMS_change_method( data, control, inform, lambda )
```

`data` is a scalar `INTENT(INOUT)` argument of type `LMS_data_type` (see §2.1.4). It is used to hold data about the factors obtained. It must not have been altered **by the user** since the last call to `LMS_form`.

`control` is a scalar `INTENT(IN)` argument of type `LMS_control_type` (see §2.1.1). Default values may be assigned by calling `LMS_initialize` prior to the first call to `LMS_setup`.

`inform` is a scalar `INTENT(OUT)` argument of type `LMS_inform_type` (see §2.1.3). A successful call to `LMS_setup` is indicated when the component `status` has the value 0. For other return values of `status`, see §2.3.

`lambda` is an OPTIONAL, `INTENT(IN)` REAL (double precision in `GALAHAD_LMS_double`) scalar that if present will be used to specify the shift  $\lambda_k$  that is used by the limited memory methods defined by `control%method = 1, 2` or 4. **Restriction:** the update will be skipped if `lambda < 0` for these methods.

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### 2.2.6 The subroutine for applying the limited-memory formula to a vector

Given the vector  $\mathbf{v}$ , the required limited-memory formula, as specified in the most recent call to `LMS_form`, `LMS_form-shift` or `LMS_change_method`, is applied to  $\mathbf{v}$  as follows:

```
CALL LMS_apply( V, U, data, control, inform )
```

`V` is a rank-one INTENT(IN) array of type default REAL that must be set on entry to hold the components of the vector  $\mathbf{v}$ .

`U` is a rank-one INTENT(OUT) array of type default REAL that will be set on exit to the result of applying the required limited-memory formula to  $\mathbf{v}$ .

`data` is a scalar INTENT(INOUT) argument of type `LMS_data_type` (see §2.1.4). It is used to hold data about the factors obtained. It must not have been altered **by the user** since the last call to `LMS_setup`.

`control` is a scalar INTENT(IN) argument of type `LMS_control_type` (see §2.1.1). Default values may be assigned by calling `LMS_initialize` prior to the first call to `LMS_setup`.

`inform` is a scalar INTENT(OUT) argument of type `LMS_inform_type` (see §2.1.3). A successful call to `LMS_apply` is indicated when the component `status` has the value 0. For other return values of `status`, see §2.3.

### 2.2.7 The termination subroutine

All previously allocated arrays are deallocated as follows:

```
CALL LMS_terminate( data, control, inform )
```

`data` is a scalar INTENT(INOUT) argument of type `LMS_data_type` exactly as for `LMS_setup`, which must not have been altered **by the user** since the last call to `LMS_initialize`. On exit, array components will have been deallocated.

`control` is a scalar INTENT(IN) argument of type `LMS_control_type` exactly as for `LMS_setup`.

`inform` is a scalar INTENT(OUT) argument of type `LMS_inform_type` exactly as for `LMS_setup`. Only the component `status` will be set on exit, and a successful call to `LMS_terminate` is indicated when this component `status` has the value 0. For other return values of `status`, see §2.3.

## 2.3 Warning and error messages

A negative value of `inform%status` on exit from `LMS_setup`, `LMS_apply` or `LMS_terminate` indicates that an error has occurred. No further calls should be made until the error has been corrected. Possible values are:

- 1. An allocation error occurred. A message indicating the offending array is written on unit `control%error`, and the returned allocation status and a string containing the name of the offending array are held in `inform%alloc-status` and `inform%bad_alloc` respectively.
- 2. A deallocation error occurred. A message indicating the offending array is written on unit `control%error` and the returned allocation status and a string containing the name of the offending array are held in `inform%alloc-status` and `inform%bad_alloc` respectively.
- 3. One of the restriction  $n > 0$ ,  $\delta > 0$  or  $\lambda \geq 0$ .  $\mathbf{s}^T \mathbf{y} > 0$  has been violated and the update has been skipped.
- 10. The matrix cannot be built with from the current vectors  $\{\mathbf{s}_k\}$  and  $\{\mathbf{y}_k\}$  and values  $\delta_k$  and  $\lambda_k$  and the update has been skipped.

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- 31. A call to subroutine `LMS_apply` has been made without a prior call to `LMS_form_shift` or `LMS_form` with `lambda` specified when `control%method = 4`, or `LMS_form_shift` has been called when `control%method = 3`, or `LMS_change_method` has been called after `control%any_method = .FALSE.` was specified when calling `LMS_setup`.

## 2.4 Further features

In this section, we describe an alternative means of setting control parameters, that is components of the variable `control` of type `LMS_control_type` (see §2.1.1), by reading an appropriate data specification file using the subroutine `LMS_read_specfile`. This facility is useful as it allows a user to change LMS control parameters without editing and recompiling programs that call LMS.

A specification file, or `specfile`, is a data file containing a number of "specification commands". Each command occurs on a separate line, and comprises a "keyword", which is a string (in a close-to-natural language) used to identify a control parameter, and an (optional) "value", which defines the value to be assigned to the given control parameter. All keywords and values are case insensitive, keywords may be preceded by one or more blanks but values must not contain blanks, and each value must be separated from its keyword by at least one blank. Values must not contain more than 30 characters, and each line of the `specfile` is limited to 80 characters, including the blanks separating keyword and value.

The portion of the specification file used by `LMS_read_specfile` must start with a "BEGIN LMS" command and end with an "END" command. The syntax of the `specfile` is thus defined as follows:

```
( .. lines ignored by LMS_read_specfile .. )
  BEGIN LMS
    keyword    value
    .....    .....
    keyword    value
  END
( .. lines ignored by LMS_read_specfile .. )
```

where `keyword` and `value` are two strings separated by (at least) one blank. The "BEGIN LMS" and "END" delimiter command lines may contain additional (trailing) strings so long as such strings are separated by one or more blanks, so that lines such as

```
BEGIN LMS SPECIFICATION
```

and

```
END LMS SPECIFICATION
```

are acceptable. Furthermore, between the "BEGIN LMS" and "END" delimiters, specification commands may occur in any order. Blank lines and lines whose first non-blank character is `!` or `*` are ignored. The content of a line after a `!` or `*` character is also ignored (as is the `!` or `*` character itself). This provides an easy manner to "comment out" some specification commands, or to comment specific values of certain control parameters.

The value of a control parameters may be of three different types, namely integer, logical or real. Integer and real values may be expressed in any relevant Fortran integer and floating-point formats (respectively). Permitted values for logical parameters are "ON", "TRUE", ".TRUE.", "T", "YES", "Y", or "OFF", "NO", "N", "FALSE", ".FALSE." and "F". Empty values are also allowed for logical control parameters, and are interpreted as "TRUE".

The specification file must be open for input when `LMS_read_specfile` is called, and the associated device number passed to the routine in `device` (see below). Note that the corresponding file is `REWINDED`, which makes it possible to combine the specifications for more than one program/routine. For the same reason, the file is not closed by `LMS_read_specfile`.

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### 2.4.1 To read control parameters from a specification file

Control parameters may be read from a file as follows:

```
CALL LMS_read_specfile( control, device )
```

`control` is a scalar `INTENT(INOUT)` argument of type `LMS_control_type` (see §2.1.1). Default values should have already been set, perhaps by calling `LMS_initialize`. On exit, individual components of `control` may have been changed according to the commands found in the specfile. Specfile commands and the component (see §2.1.1) of `control` that each affects are given in Table 2.1.

command	component of control	value type
error-printout-device	%error	integer
printout-device	%out	integer
print-level	%print_level	integer
limited-memory-length	%memory_length	integer
limited-memory-method	%method	integer
allow-any-method	%any_method	logical
space-critical	%space_critical	logical
deallocate-error-fatal	%deallocate_error_fatal	logical
output-line-prefix	%prefix	character

Table 2.1: Specfile commands and associated components of `control`.

`device` is a scalar `INTENT(IN)` argument of type `default INTEGER`, that must be set to the unit number on which the specfile has been opened. If `device` is not open, `control` will not be altered and execution will continue, but an error message will be printed on unit `control%error`.

### 2.5 Information printed

If `control%print_level` is positive, information about the progress of the algorithm will be printed on unit `control%out`. If `control%print_level`  $\geq 1$ , statistics concerning the formation of **R** as well as warning and error messages will be reported.

## 3 GENERAL INFORMATION

**Use of common:** None.

**Workspace:** Provided automatically by the module.

**Other routines called directly:** None.

**Other modules used directly:** LMS calls the GALAHAD packages `GALAHAD_CLOCK`, `GALAHAD_SYMBOLS`, `GALAHAD_SPACE`, `GALAHAD_LAPACK_interface`, `GALAHAD_BLAS_interface` and `GALAHAD_SPECFILE`,

**Input/output:** Output is under control of the arguments `control%error`, `control%out` and `control%print_level`.

**Restrictions:**  $n > 0$ ,  $\delta > 0$ ,  $\lambda \geq 0$ .

**Portability:** ISO Fortran 95 + TR 15581 or Fortran 2003. The package is thread-safe.

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## 4 METHOD

Given a sequence of vectors  $\{\mathbf{s}_k\}$  and  $\{\mathbf{y}_k\}$  and scale factors  $\delta_k$ , a limited-memory secant approximation  $\mathbf{H}_k$  is chosen so that  $\mathbf{H}_{\max(k-m,0)} = \delta_k \mathbf{I}$ ,  $\mathbf{H}_{k-j} \mathbf{s}_{k-j} = \mathbf{y}_{k-j}$  and  $\|\mathbf{H}_{k-j+1} - \mathbf{H}_{k-j}\|$  is “small” for  $j = \min(k-1, m-1), \dots, 0$ . Different ways of quantifying “small” distinguish different methods, but the crucial observation is that it is possible to construct  $\mathbf{H}_k$  quickly from  $\{\mathbf{s}_k\}$  and  $\{\mathbf{y}_k\}$  and  $\delta_k$ , and to apply it and its inverse to a given vector  $\mathbf{v}$ . It is also possible to apply similar formulae to the “shifted” matrix  $\mathbf{H}_k + \lambda_k \mathbf{I}$  that occurs in trust-region methods.

The basic methods are those given by

R. H. Byrd, J. Nocedal and R. B. Schnabel (1994) Representations of quasi-Newton matrices and their use in limited memory methods. *Math. Programming*, **63**(2) 129–156,

with obvious extensions.

## 5 EXAMPLE OF USE

Suppose that we generate random vectors  $\{\mathbf{s}_k\}$  and  $\{\mathbf{y}_k\}$  and scale factors  $\delta_k$ , that we build the limited-memory BFGS matrix  $\mathbf{H}_k$  and its inverse  $\mathbf{H}_k^{-1}$  and that we apply  $\mathbf{H}_k$  and then  $\mathbf{H}_k^{-1}$  to a given vector  $\mathbf{v}$ . Suppose further, that at some stage, we instead apply the inverse  $(\mathbf{H}_k + \lambda_k \mathbf{I})^{-1}$  with  $\lambda_k = 0$ . Then we may use the following code; of course since we have the identities  $\mathbf{v} = \mathbf{H}_k^{-1}(\mathbf{H}_k \mathbf{v})$  and  $\mathbf{v} = (\mathbf{H}_k + \lambda_k \mathbf{I})^{-1}(\mathbf{H}_k \mathbf{v})$  when  $\lambda_k = 0$ , we expect to recover the original  $\mathbf{v}$  after every step:

```
! THIS VERSION: GALAHAD 2.6 - 12/06/2014 AT 15:30 GMT.
PROGRAM GALAHAD_LMS_example
USE GALAHAD_LMS_double           ! double precision version
USE GALAHAD_rand_double
IMPLICIT NONE
INTEGER, PARAMETER :: wp = KIND( 1.0D+0 ) ! set precision
INTEGER, PARAMETER :: n = 5, m = 3
TYPE ( LMS_data_type ) :: data, data2
TYPE ( LMS_control_type ) :: control, control2
TYPE ( LMS_inform_type ) :: inform, inform2
REAL ( KIND = wp ), DIMENSION( n ) :: S, Y, U, V
INTEGER :: iter, fail
REAL ( KIND = wp ) :: delta, lambda, sts, stv, ratio, error
TYPE ( RAND_seed ) :: seed
CALL RAND_initialize( seed ) ! Initialize the random generator word
CALL LMS_initialize( data, control, inform ) ! initialize data
control%memory_length = m ! set the memory length
control2 = control
control%method = 1 ! start with L-BFGS
CALL LMS_setup( n, data, control, inform )
control2%method = 3 ! then inverse L-BFGS
control2%any_method = .TRUE. ! allow the 2nd update to change method
CALL LMS_setup( n, data2, control2, inform2 )
fail = 0 ! count the failures
DO iter = 1, 5 * n
    IF ( iter == 3 * n ) THEN ! switch to inverse shifted L-BFGS
        CALL LMS_setup( n, data, control, inform )
        control2%method = 4
        CALL LMS_setup( n, data2, control2, inform2 )
    END IF
    CALL RAND_random_real( seed, .FALSE., S ) ! pick random S, Y and delta
    CALL RAND_random_real( seed, .FALSE., Y )
```

---

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```

IF ( DOT_PRODUCT( S, Y ) < 0.0_wp ) Y = - Y ! ensure that S^T Y is positive
CALL RAND_random_real( seed, .TRUE., delta )
CALL LMS_form( S, Y, delta, data, control, inform ) ! update the model
IF ( inform%status /= 0 ) THEN
  WRITE( 6, "( ' update error, status = ', I0 )" ) inform%status
  fail = fail + 1 ; CYCLE
END IF
V = 1.0_wp ! form the first product with the vector ones
CALL LMS_apply( V, U, data, control, inform ) ! form the required product
IF ( inform%status /= 0 ) THEN
  WRITE( 6, "( ' apply error, status = ', I0 )" ) inform%status
  fail = fail + 1 ; CYCLE
END IF
CALL LMS_form( S, Y, delta, data2, control2, inform2 ) ! update model 2
IF ( inform2%status /= 0 ) THEN
  WRITE( 6, "( ' update error, status = ', I0 )" ) inform2%status
  fail = fail + 1 ; CYCLE
END IF
IF ( control2%method == 4 ) THEN
  lambda = 0.0_wp ! apply the shifted L_BFGS (inverse) with zero shift
  CALL LMS_form_shift( lambda, data2, control2, inform2 )
  IF ( inform2%status /= 0 ) THEN
    WRITE( 6, "( ' update error, status = ', I0 )" ) inform2%status
    fail = fail + 1 ; CYCLE
  END IF
END IF
! note, the preceeding two calls could have been condensed as
! CALL LMS_form( S, Y, delta, data2, control2, inform2, lambda = 0.0_wp )
CALL LMS_apply( U, V, data2, control2, inform2 ) ! form the new product
IF ( inform2%status /= 0 ) THEN
  WRITE( 6, "( ' apply error, status = ', I0 )" ) inform2%status
  fail = fail + 1 ; CYCLE
END IF
IF ( MAXVAL( ABS( V - 1.0_wp ) ) > 0.00001_wp ) fail = fail + 1
END DO
IF ( fail == 0 ) THEN ! check for overall success
  WRITE( 6, "( ' no failures ' )" )
ELSE
  WRITE( 6, "( I0, ' failures ' )" ) fail
END IF
CALL LMS_terminate( data, control, inform ) ! delete internal workspace
CALL LMS_terminate( data2, control2, inform2 )
END PROGRAM GALAHAD_LMS_example

```

This produces the following output:

```
no failures
```

---

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