

Package ‘funcharts’

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Type Package

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| | |
|-----|-------------------------|
| air | <i>Air quality data</i> |
|-----|-------------------------|

Description

This data set has been included from the R package `FRegSigCom`. The original .RData file is available at <https://github.com/cran/FRegSigCom/blob/master/data/air.RData>.

Data collected hourly in 355 days (days with missing values removed) in a significantly polluted area within an Italian city.

Usage

```
data("air")
```

Format

A list of 7 matrices with 355 rows and 24 columns:

NO2 Hourly observation of concentration level of NO2 in 355 days

CO Hourly observation of concentration level of CO in 355 days

NMHC Hourly observation of concentration level of NMHC in 355 days

NOx Hourly observation of concentration level of NOx in 355 days

C6H6 Hourly observation of concentration level of C6H6 in 355 days

temperature Hourly observation of concentration level of temperature in 355 days

humidity Hourly observation of concentration level of humidity in 355 days

Source

<https://archive.ics.uci.edu/ml/datasets/Air+quality>

References

De Vito, S., Massera E., Piga M., Martinotto L. and Di Francia G. (2008). On field calibration of an electronic nose for benzene estimation in an urban pollution monitoring scenario *Sensors and Actuators B: Chemical*, 129: 50-757. doi:10.1016/j.snb.2007.09.060

Xin Qi and Ruiyan Luo (2019). Nonlinear function on function additive model with multiple predictor curves. *Statistica Sinica*, 29:719-739. doi:10.5705/ss.202017.0249

AMFEWMA_PhaseI

Adaptive Multivariate Functional EWMA control chart - Phase I

Description

This function performs Phase I of the Adaptive Multivariate Functional EWMA (AMFEWMA) control chart proposed by Capezza et al. (2024)

Usage

```
AMFEWMA_PhaseI(
  mfdobj,
  mfdobj_tuning,
  lambda = NULL,
  k = NULL,
  ARL0 = 200,
  bootstrap_pars = list(n_seq = 200, l_seq = 2000),
  optimization_pars = list(lambda_grid = c(0.1, 0.2, 0.3, 0.5, 1), k_grid = c(1, 2, 3,
    4), epsilon = 0.1, sd_small = 0.25, sd_big = 2),
  discrete_grid_length = 25,
  score_function = "huber",
  fev = 0.9,
  n_skip = 100
)
```

Arguments

| | |
|-----------------------------------|---|
| <code>mfdobj</code> | An object of class <code>mfd</code> containing the Phase I multivariate functional data set, to be used to train the multivariate functional principal component analysis model. |
| <code>mfdobj_tuning</code> | An object of class <code>mfd</code> containing the Phase I multivariate functional data set, to be used as tuning data set to estimate the AMFEWMA control chart limit. |
| <code>lambda</code> | lambda parameter to be used in the score function. See Equation (7) or (8) of Capezza et al. (2024). If it is provided, it must be a number between zero and one. If NULL, it is chosen through the selected according to the optimization procedure presented in Section 2.4 of Capezza et al. (2024). In this case, it is chosen among the values of <code>optimization_pars\$lambda_grid</code> . Default value is NULL. |
| <code>k</code> | k parameter to be used in the score function. See Equation (7) or (8) of Capezza et al. (2024). If it is provided, it must be a number greater than zero. If NULL, it is chosen through the selected according to the optimization procedure presented in Section 2.4 of Capezza et al. (2024). In this case, it is chosen among the values of <code>optimization_pars\$k_grid</code> . Default value is NULL. |
| <code>ARL0</code> | The nominal in-control average run length. Default value is 200. |
| <code>bootstrap_pars</code> | Parameters of the bootstrap procedure described in Section 2.4 of Capezza et al. (2024) for the estimation of the control chart limit. It must be a list with two arguments. <code>n_seq</code> is the number of bootstrap sequences to be generated. <code>l_seq</code> is the length of each bootstrap sequence, i.e., the number of observations to be sampled with replacement from the tuning set. Default value is <code>list(n_seq = 200, l_seq = 2000)</code> . |
| <code>optimization_pars</code> | Parameters to be used in the optimization procedure described in Section 2.4 of Capezza et al. (2024) for the selection of the parameters lambda and k. It must be a list of the following parameters. <code>lambda_grid</code> contains the possible values of the parameter lambda. <code>k_grid</code> contains the possible values of the parameter k. <code>epsilon</code> is the parameter used in Equation (10) of Capezza et al. (2024). When performing the parameter optimization, first the parameters lambda and k are selected to minimize the ARL with respect to a large shift, then the same parameters are chosen to minimize the ARL with respect to a small shift, given that the resulting ARL with respect to the previous large shift does not increase, in percentage, more than <code>epsilon*100</code> . Default value is 0.1. <code>sd_small</code> is a positive constant that multiplies the standard deviation function to define the small shift <code>delta_1</code> in Section 2.4 of Capezza et al. (2024). In fact, the small shift is defined as $\delta_1(t) = \mu_0(t) + sd_small * \sigma(t)$, where $\mu_0(t)$ is the estimated in-control mean function and $\sigma(t)$ is the estimated standard deviation function. Default value is 0.25. <code>sd_big</code> is a positive constant that multiplies the standard deviation function to define the large shift <code>delta_2</code> in Section 2.4 of Capezza et al. (2024). In fact, the large shift is defined as $\delta_2(t) = \mu_0(t) + sd_large * \sigma(t)$, where $\mu_0(t)$ is the estimated in-control mean function and $\sigma(t)$ is the estimated standard deviation function. Default value is 2. |
| <code>discrete_grid_length</code> | The number of equally spaced argument values at which the <code>mfd</code> objects are discretized. Default value is 25. |

| | |
|----------------|---|
| score_function | Score function to be used in Equation (7) or (8) of Capezza et al. (2024), to calculate the weighting parameter of the EWMA statistic for each observation of the sequence. Two values are possible. If "huber", it uses the score function (7) inspired by the Huber's function. If "tukey", it uses the score function (8) inspired by the Tukey's bisquare function. |
| fev | Number between 0 and 1 denoting the fraction of variability that must be explained by the principal components to be selected after applying multivariate functional principal component analysis on mfdobj. Default is 0.9. |
| n_skip | The upper control limit of the AMFEWMA control chart is set to achieve a desired in-control ARL, evaluated after the monitoring statistic has reached steady state. A monitoring statistic is in a steady state if the process has been in control long enough for the effect of the starting value to become negligible (Lucas and Saccucci, 1990). In this regard, the first n_skip observations are excluded from the calculation of the run length. Default value is 100. |

Value

A list with the following elements. lambda is the selected lambda parameter. k is the selected k parameter. mod_1 contains the estimated Phase I model. It is a list with the following elements.

- mfdobj the mfdobj object passed as input to this function,
- mfdobj_tuning the mfdobj_tuning object passed as input to this function,
- inv_sigmaY_reg: the matrix containing the discretized version of the function $K^{*(s,t)}$ defined in Equation (9) of Capezza et al. (2024),
- mean_mfdobj: the estimated mean function,
- h: the calculated upper control limit of the AMFEWMA control chart,
- ARL0: the estimated in-control ARL, which should be close to the nominal value passed as input to this function,
- lambda: the lambda parameter selected by the optimization procedure described in Section 2.4 of Capezza et al. (2024).
- k: The function $C_j(t)=k \sigma_j(t)$ appearing in the score functions (7) and (8) of Capezza et al. (2024).
- grid_points: the grid containing the points over which the functional data are discretized before computing the AMFEWMA monitoring statistic and estimating all the model parameters.
- V2_mat: the $n_{seq} \times l_{seq}$ matrix containing, in each column, the AMFEWMA monitoring statistic values of each bootstrap sequence. This matrix is used to set the control chart limit h to ensure that the desired average run length is achieved.
- n_skip: the n_skip input parameter passed to this function,
- huber: if the input parameter score_function is "huber", this is TRUE, else is FALSE,
- vectors: the discretized eigenfunctions $\psi_l(t)$ of the covariance function, appearing in Equation (9) of Capezza et al. (2024).
- values: the eigenvalues ρ_l of the covariance function, appearing in Equation (9) of Capezza et al. (2024).

Author(s)

C. Capezza, F. Centofanti

References

Capezza, C., Capizzi, G., Centofanti, F., Lepore, A., Palumbo, B. (2024) An Adaptive Multivariate Functional EWMA Control Chart. To appear in *Journal of Quality Technology*, doi:10.1080/00224065.2024.2383674.

Lucas, J. M., Saccucci, M. S. (1990) Exponentially weighted moving average control schemes: properties and enhancements. *Technometrics*, 32(1), 1-12.

Examples

```
## Not run: set.seed(0)
library(funcharts)
dat_I <- simulate_mfd(nobs = 1000,
                     correlation_type_x = c("Bessel", "Bessel", "Bessel"),
                     sd_x = c(0.3, 0.3, 0.3))
dat_tun <- simulate_mfd(nobs = 1000,
                       correlation_type_x = c("Bessel", "Bessel", "Bessel"),
                       sd_x = c(0.3, 0.3, 0.3))
dat_II <- simulate_mfd(nobs = 200,
                      correlation_type_x = c("Bessel", "Bessel", "Bessel"),
                      shift_type_x = c("C", "C", "C"),
                      d_x = c(2, 2, 2),
                      sd_x = c(0.3, 0.3, 0.3))
mfdobj_I <- get_mfd_list(dat_I$X_list)
mfdobj_tun <- get_mfd_list(dat_tun$X_list)
mfdobj_II <- get_mfd_list(dat_II$X_list)

p <- plot_mfd(mfdobj_I[1:100])
lines_mfd(p, mfdobj_II, col = "red")

mod <- AMFEWMA_PhaseI(mfdobj = mfdobj_I, mfdobj_tuning = mfdobj_tun)
print(mod$k)
cc <- AMFEWMA_PhaseII(mfdobj_2 = rbind_mfd(mfdobj_I[1:100], mfdobj_II),
                     mod_1 = mod)
plot_control_charts(cc$cc, nobsI = 100)

## End(Not run)
```

Description

This function performs Phase II of the Adaptive Multivariate Functional EWMA (AMFEWMA) control chart proposed by Capezza et al. (2024)

Usage

```
AMFEWMA_PhaseII(mfdobj_2, mod_1, n_seq_2 = 1, l_seq_2 = 2000)
```

Arguments

| | |
|----------|---|
| mfdobj_2 | An object of class <code>mfd</code> containing the Phase II multivariate functional data set, to be monitored with the AMFEWMA control chart. |
| mod_1 | The output of the Phase I achieved through the AMFEWMA_PhaseI function. |
| n_seq_2 | If it is 1, the Phase II monitoring statistic is calculated on the data sequence. If it is an integer number larger than 1, a number <code>n_seq_2</code> of bootstrap sequences are sampled with replacement from <code>mfdobj_2</code> to allow uncertainty quantification on the estimation of the run length. Default value is 1. |
| l_seq_2 | If <code>n_seq_2</code> is larger than 1, this parameter sets the length of each bootstrap sequence to be generated. Default value is 2000 (which is ignored if the default value |

Value

A list with the following elements.

- `ARL_2`: the average run length estimated over the bootstrap sequences. If `n_seq_2` is 1, it is simply the run length observed over the Phase II sequence, i.e., the number of observations up to the first alarm,
- `RL`: the run length observed over the Phase II sequence, i.e., the number of observations up to the first alarm,
- `V2`: a list with length `n_seq_2`, containing the AMFEWMA monitoring statistic in Equation (8) of Capezza et al. (2024), calculated in each bootstrap sequence, until the first alarm.
- `cc`: a data frame with the information needed to plot the AMFEWMA control chart in Phase II, with the following columns. `id` contains the id of each multivariate functional observation, `amfewma_monitoring_statistic` contains the AMFEWMA monitoring statistic values calculated on the Phase II sequence, `amfewma_monitoring_statistic_lim` is the upper control limit.

Author(s)

C. Capezza, F. Centofanti

References

Capezza, C., Capizzi, G., Centofanti, F., Lepore, A., Palumbo, B. (2024) An Adaptive Multivariate Functional EWMA Control Chart. To appear in *Journal of Quality Technology*, doi:[10.1080/00224065.2024.2383674](https://doi.org/10.1080/00224065.2024.2383674).

Examples

```
## Not run: set.seed(0)
library(funcharts)
dat_I <- simulate_mfd(nobs = 1000,
                     correlation_type_x = c("Bessel", "Bessel", "Bessel"),
                     sd_x = c(0.3, 0.3, 0.3))
dat_tun <- simulate_mfd(nobs = 1000,
                       correlation_type_x = c("Bessel", "Bessel", "Bessel"),
                       sd_x = c(0.3, 0.3, 0.3))
dat_II <- simulate_mfd(nobs = 200,
                      correlation_type_x = c("Bessel", "Bessel", "Bessel"),
                      shift_type_x = c("C", "C", "C"),
                      d_x = c(2, 2, 2),
                      sd_x = c(0.3, 0.3, 0.3))
mfdobj_I <- get_mfd_list(dat_I$X_list)
mfdobj_tun <- get_mfd_list(dat_tun$X_list)
mfdobj_II <- get_mfd_list(dat_II$X_list)

p <- plot_mfd(mfdobj_I[1:100])
lines_mfd(p, mfdobj_II, col = "red")

mod <- AMFEWMA_PhaseI(mfdobj = mfdobj_I, mfdobj_tuning = mfdobj_tun)
print(mod$lambda)
print(mod$k)
cc <- AMFEWMA_PhaseII(mfdobj_2 = rbind_mfd(mfdobj_I[1:100], mfdobj_II),
                     mod_1 = mod)
plot_control_charts(cc$cc, nobsI = 100)

## End(Not run)
```

cbind_mfd

Bind variables of two Multivariate Functional Data Objects

Description

Bind variables of two Multivariate Functional Data Objects

Usage

```
cbind_mfd(mfdobj1, mfdobj2)
```

Arguments

mfdobj1 An object of class `mfd`, with the same number of replications of `mfdobj2` and different variable names with respect to `mfdobj2`.

mfdobj2 An object of class `mfd`, with the same number of replications of `mfdobj1`, and different variable names with respect to `mfdobj1`.

Value

An object of class `mfd`, whose replications are the same of `mfdobj1` and `mfdobj2` and whose functional variables are the union of the functional variables in `mfdobj1` and `mfdobj2`.

Examples

```
library(funcharts)
mfdobj1 <- data_sim_mfd(nvar = 3)
mfdobj2 <- data_sim_mfd(nvar = 2)
dimnames(mfdobj2$coefs)[[3]] <- mfdobj2$fdnames[[3]] <- c("var10", "var11")

plot_mfd(mfdobj1)
plot_mfd(mfdobj2)
mfdobj_cbind <- cbind_mfd(mfdobj1, mfdobj2)
plot_mfd(mfdobj_cbind)
```

control_charts_pca *T2 and SPE control charts for multivariate functional data*

Description

This function builds a data frame needed to plot the Hotelling's T^2 and squared prediction error (SPE) control charts based on multivariate functional principal component analysis (MFPCA) performed on multivariate functional data, as Capezza et al. (2020) for the multivariate functional covariates. The training data have already been used to fit the model. An optional tuning data set can be provided to estimate the control chart limits. A phase II data set contains the observations to be monitored with the control charts.

Usage

```
control_charts_pca(
  pca,
  components = NULL,
  tuning_data = NULL,
  newdata,
  alpha = 0.05,
  limits = "standard",
  seed,
  nfold = 5,
  ncores = 1,
  tot_variance_explained = 0.9,
  single_min_variance_explained = 0,
  absolute_error = FALSE
)
```

Arguments

| | |
|-------------------------------|--|
| pca | An object of class <code>pca_mfd</code> obtained by doing MFPCA on the training set of multivariate functional data. |
| components | A vector of integers with the components over which to project the multivariate functional data. If this is not <code>NULL</code> , the arguments <code>single_min_variance_explained</code> and <code>tot_variance_explained</code> are ignored. If <code>NULL</code> , components are selected such that the total fraction of variance explained by them is at least equal to the argument <code>tot_variance_explained</code> , where only components explaining individually a fraction of variance at least equal to the argument <code>single_min_variance_explained</code> are considered to be retained. Default is <code>NULL</code> . |
| tuning_data | An object of class <code>mfd</code> containing the tuning set of the multivariate functional data, used to estimate the T2 and SPE control chart limits. If <code>NULL</code> , the training data, i.e. the data used to fit the MFPCA model, are also used as the tuning data set, i.e. <code>tuning_data=pca\$data</code> . Default is <code>NULL</code> . |
| newdata | An object of class <code>mfd</code> containing the phase II set of the multivariate functional data to be monitored. |
| alpha | If it is a number between 0 and 1, it defines the overall type-I error probability and the Bonferroni correction is applied by setting the type-I error probability in the two control charts equal to $\alpha/2$. If you want to set manually the Type-I error probabilities in the two control charts, then the argument <code>alpha</code> must be a named list with two elements, named <code>T2</code> and <code>spe</code> , respectively, each containing the desired Type I error probability of the corresponding control chart. Default value is 0.05. |
| limits | A character value. If <code>"standard"</code> , it estimates the control limits on the tuning data set. If <code>"cv"</code> , the function calculates the control limits only on the training data using cross-validation using <code>calculate_cv_limits</code> . Default is <code>"standard"</code> . |
| seed | If <code>limits=="cv"</code> , since the split in the <code>k</code> groups is random, you can fix a seed to ensure reproducibility. Deprecated: use <code>set.seed()</code> before calling the function for reproducibility. |
| nfold | If <code>limits=="cv"</code> , this gives the number of groups <code>k</code> used for <code>k</code> -fold cross-validation. If it is equal to the number of observations in the training data set, then we have leave-one-out cross-validation. Otherwise, this argument is ignored. |
| ncores | If <code>limits=="cv"</code> , if you want perform the analysis in the <code>k</code> groups in parallel, give the number of cores/threads. Otherwise, this argument is ignored. |
| tot_variance_explained | The minimum fraction of variance that has to be explained by the set of multivariate functional principal components retained into the MFPCA model fitted on the functional covariates. Default is 0.9. |
| single_min_variance_explained | The minimum fraction of variance that has to be explained by each multivariate functional principal component such that it is retained into the MFPCA model. Default is 0. |
| absolute_error | If <code>FALSE</code> , the SPE statistic, which monitors the principal components not retained in the MFPCA model, is calculated as the sum of the integrals of the |

squared prediction error functions, obtained as the difference between the actual functions and their approximation after projection over the selected principal components. If TRUE, the SPE statistic is calculated by replacing the square of the prediction errors with the absolute value, as proposed by Capizzi and Masarotto (2018). Default value is FALSE.

Value

A data.frame with as many rows as the number of multivariate functional observations in the phase II data set and the following columns:

- one id column identifying the multivariate functional observation in the phase II data set,
- one T2 column containing the Hotelling T2 statistic calculated for all observations,
- one column per each functional variable, containing its contribution to the T2 statistic,
- one spe column containing the SPE statistic calculated for all observations,
- one column per each functional variable, containing its contribution to the SPE statistic,
- T2_lim gives the upper control limit of the Hotelling's T2 control chart,
- one contribution_T2*_lim column per each functional variable giving the limits of the contribution of that variable to the Hotelling's T2 statistic,
- spe_lim gives the upper control limit of the SPE control chart
- one contribution_spe*_lim column per each functional variable giving the limits of the contribution of that variable to the SPE statistic.

References

Capezza C, Lepore A, Menafoglio A, Palumbo B, Vantini S. (2020) Control charts for monitoring ship operating conditions and CO2 emissions based on scalar-on-function regression. *Applied Stochastic Models in Business and Industry*, 36(3):477–500. doi:10.1002/asmb.2507

Capizzi, G., & Masarotto, G. (2018). Phase I distribution-free analysis with the R package dfphase1. In *Frontiers in Statistical Quality Control 12* (pp. 3-19). Springer International Publishing.

See Also

[regr_cc_fof](#)

Examples

```
library(funcharts)
data("air")
air <- lapply(air, function(x) x[1:220], , drop = FALSE)
fun_covariates <- c("CO", "temperature")
mfdobj_x <- get_mfd_list(air[fun_covariates],
                       n_basis = 15,
                       lambda = 1e-2)

y <- rowMeans(air$NO2)
y1 <- y[1:100]
y_tuning <- y[101:200]
y2 <- y[201:220]
```

```

mfdobj_x1 <- mfdobj_x[1:100]
mfdobj_x_tuning <- mfdobj_x[101:200]
mfdobj_x2 <- mfdobj_x[201:220]
pca <- pca_mfd(mfdobj_x1)
cclist <- control_charts_pca(pca = pca,
                           tuning_data = mfdobj_x_tuning,
                           newdata = mfdobj_x2)

plot_control_charts(cclist)

```

control_charts_pca_mfd_real_time

Real-time T2 and SPE control charts for multivariate functional data

Description

This function produces a list of data frames, each of them is produced by [control_charts_pca](#) and is needed to plot control charts for monitoring multivariate functional covariates each evolving up to an intermediate domain point.

Usage

```

control_charts_pca_mfd_real_time(
  pca_list,
  components_list = NULL,
  mfdobj_x_test,
  mfdobj_x_tuning = NULL,
  alpha = 0.05,
  limits = "standard",
  seed,
  nfold = NULL,
  tot_variance_explained = 0.9,
  single_min_variance_explained = 0,
  absolute_error = FALSE,
  ncores = 1
)

```

Arguments

pca_list A list of lists produced by [pca_mfd_real_time](#), containing a list of multivariate functional principal component analysis models estimated on functional data each evolving up to an intermediate domain point.

components_list A list of components given as input to [pca_mfd](#) for each intermediate domain point.

| | |
|-------------------------------|--|
| mfdobj_x_test | A list created using get_mfd_df_real_time or get_mfd_list_real_time , denoting a list of functional data objects in the phase II monitoring data set, each evolving up to an intermediate domain point, with observations of the multivariate functional data. The length of this list and <code>pca_list</code> must be equal, and their elements in the same position in the list must correspond to the same intermediate domain point. |
| mfdobj_x_tuning | A list created using get_mfd_df_real_time or get_mfd_list_real_time , denoting a list of functional data objects in the tuning data set (used to estimate control chart limits), each evolving up to an intermediate domain point, with observations of the multivariate functional data. The length of this list and <code>pca_list</code> must be equal, and their elements in the same position in the list must correspond to the same intermediate domain point. If NULL, the training data, i.e. the functional data in <code>pca_list</code> , are also used as the tuning data set. Default is NULL. |
| alpha | See control_charts_pca . |
| limits | See control_charts_pca . |
| seed | Deprecated: See control_charts_pca . |
| nfold | See control_charts_pca . |
| tot_variance_explained | See control_charts_pca . |
| single_min_variance_explained | See control_charts_pca . |
| absolute_error | See control_charts_pca . |
| ncores | If you want parallelization, give the number of cores/threads to be used when creating objects separately for different instants. |

Value

A list of data.frames each produced by [control_charts_pca](#), corresponding to a given instant.

See Also

[pca_mfd_real_time](#), [control_charts_pca](#)

Examples

```
library(funcharts)
data("air")
air1 <- lapply(air, function(x) x[1:8, , drop = FALSE])
air2 <- lapply(air, function(x) x[9:10, , drop = FALSE])
mfdobj_x1_list <- get_mfd_list_real_time(air1[c("CO", "temperature")],
                                       n_basis = 15,
                                       lambda = 1e-2,
                                       k_seq = c(0.5, 1))
mfdobj_x2_list <- get_mfd_list_real_time(air2[c("CO", "temperature")],
                                       n_basis = 15,
                                       lambda = 1e-2,
```

```

                                k_seq = c(0.5, 1))
pca_list <- pca_mfd_real_time(mfdobj_x1_list)

cclist <- control_charts_pca_mfd_real_time(
  pca_list = pca_list,
  components_list = 1:3,
  mfdobj_x_test = mfdobj_x2_list)
plot_control_charts_real_time(cclist, 1)

```

control_charts_sof_pc *Control charts for monitoring a scalar quality characteristic adjusted for by the effect of multivariate functional covariates*

Description

This function builds a data frame needed to plot control charts for monitoring a monitoring a scalar quality characteristic adjusted for the effect of multivariate functional covariates based on scalar-on-function regression, as proposed in Capezza et al. (2020).

In particular, this function provides:

- the Hotelling's T2 control chart,
- the squared prediction error (SPE) control chart,
- the scalar regression control chart.

This function calls `control_charts_pca` for the control charts on the multivariate functional covariates and `regr_cc_sof` for the scalar regression control chart.

The training data have already been used to fit the model. An optional tuning data set can be provided that is used to estimate the control chart limits. A phase II data set contains the observations to be monitored with the control charts.

Usage

```

control_charts_sof_pc(
  mod,
  y_test,
  mfdobj_x_test,
  mfdobj_x_tuning = NULL,
  alpha = list(T2 = 0.0125, spe = 0.0125, y = 0.025),
  limits = "standard",
  seed,
  nfold = NULL,
  ncores = 1
)

```

Arguments

| | |
|------------------------------|---|
| <code>mod</code> | A list obtained as output from <code>sof_pc</code> , i.e. a fitted scalar-on-function linear regression model. |
| <code>y_test</code> | A numeric vector containing the observations of the scalar response variable in the phase II data set. |
| <code>mfdobj_x_test</code> | An object of class <code>mfd</code> containing the phase II data set of the functional covariates observations. |
| <code>mfdobj_x_tuning</code> | An object of class <code>mfd</code> containing the tuning set of the multivariate functional data, used to estimate the T2 and SPE control chart limits. If <code>NULL</code> , the training data, i.e. the data used to fit the MFPCA model, are also used as the tuning data set, i.e. <code>tuning_data=pca\$data</code> . Default is <code>NULL</code> . |
| <code>alpha</code> | A named list with three elements, named <code>T2</code> , <code>spe</code> , and <code>y</code> , respectively, each containing the desired Type I error probability of the corresponding control chart (<code>T2</code> corresponds to the T2 control chart, <code>spe</code> corresponds to the SPE control chart, <code>y</code> corresponds to the scalar regression control chart). Note that at the moment you have to take into account manually the family-wise error rate and adjust the two values accordingly. See Capezza et al. (2020) for additional details. Default value is <code>list(T2 = 0.0125, spe = 0.0125, y = 0.025)</code> . |
| <code>limits</code> | A character value. If <code>"standard"</code> , it estimates the control limits on the tuning data set. If <code>"cv"</code> , the function calculates the control limits only on the training data using cross-validation using <code>calculate_cv_limits</code> . Default is <code>"standard"</code> . |
| <code>seed</code> | If <code>limits=="cv"</code> , since the split in the <code>k</code> groups is random, you can fix a seed to ensure reproducibility. Deprecated: use <code>set.seed()</code> before calling the function for reproducibility. |
| <code>nfold</code> | If <code>limits=="cv"</code> , this gives the number of groups <code>k</code> used for <code>k</code> -fold cross-validation. If it is equal to the number of observations in the training data set, then we have leave-one-out cross-validation. Otherwise, this argument is ignored. |
| <code>ncores</code> | If <code>limits=="cv"</code> , if you want perform the analysis in the <code>k</code> groups in parallel, give the number of cores/threads. Otherwise, this argument is ignored. |

Value

A `data.frame` with as many rows as the number of multivariate functional observations in the phase II data set and the following columns:

- one `id` column identifying the multivariate functional observation in the phase II data set,
- one `T2` column containing the Hotelling T2 statistic calculated for all observations,
- one column per each functional variable, containing its contribution to the T2 statistic,
- one `spe` column containing the SPE statistic calculated for all observations,
- one column per each functional variable, containing its contribution to the SPE statistic,
- `T2_lim` gives the upper control limit of the Hotelling's T2 control chart,
- one `contribution_T2*_lim` column per each functional variable giving the limits of the contribution of that variable to the Hotelling's T2 statistic,

- `spe_lim` gives the upper control limit of the SPE control chart
- one `contribution_spe*_lim` column per each functional variable giving the limits of the contribution of that variable to the SPE statistic.
- `y_hat`: the predictions of the response variable corresponding to `mfdobj_x_new`,
- `y`: the same as the argument `y_new` given as input to this function,
- `lwr`: lower limit of the 1-alpha prediction interval on the response,
- `pred_err`: prediction error calculated as `y-y_hat`,
- `pred_err_sup`: upper limit of the 1-alpha prediction interval on the prediction error,
- `pred_err_inf`: lower limit of the 1-alpha prediction interval on the prediction error.

Author(s)

C. Capezza

See Also

[control_charts_pca](#), [regr_cc_sof](#)

Examples

```
## Not run:
#' library(funcharts)
data("air")
air <- lapply(air, function(x) x[201:300, , drop = FALSE])
fun_covariates <- c("CO", "temperature")
mfdobj_x <- get_mfd_list(air[fun_covariates],
                       n_basis = 15,
                       lambda = 1e-2)

y <- rowMeans(air$N02)
y1 <- y[1:60]
y2 <- y[91:100]
mfdobj_x1 <- mfdobj_x[1:60]
mfdobj_x_tuning <- mfdobj_x[61:90]
mfdobj_x2 <- mfdobj_x[91:100]
mod <- sof_pc(y1, mfdobj_x1)
cclist <- control_charts_sof_pc(mod = mod,
                               y_test = y2,
                               mfdobj_x_test = mfdobj_x2,
                               mfdobj_x_tuning = mfdobj_x_tuning)

plot_control_charts(cclist)

## End(Not run)
```

 control_charts_sof_pc_real_time

Real-time scalar-on-function regression control charts

Description

This function is deprecated. Use [regr_cc_sof_real_time](#). This function produces a list of data frames, each of them is produced by [control_charts_sof_pc](#) and is needed to plot control charts for monitoring in real time a scalar quality characteristic adjusted for by the effect of multivariate functional covariates.

Usage

```
control_charts_sof_pc_real_time(
  mod_list,
  y_test,
  mfdobj_x_test,
  mfdobj_x_tuning = NULL,
  alpha = list(T2 = 0.0125, spe = 0.0125, y = 0.025),
  limits = "standard",
  seed,
  nfold = NULL,
  ncores = 1
)
```

Arguments

- | | |
|-----------------|--|
| mod_list | A list of lists produced by sof_pc_real_time , containing a list of scalar-on-function linear regression models estimated on functional data each evolving up to an intermediate domain point. |
| y_test | A numeric vector containing the observations of the scalar response variable in the phase II monitoring data set. |
| mfdobj_x_test | A list created using get_mfd_df_real_time or get_mfd_list_real_time , denoting a list of functional data objects in the phase II monitoring data set, each evolving up to an intermediate domain point, with observations of the multivariate functional covariates. The length of this list and <code>mod_list</code> must be equal, and their elements in the same position in the list must correspond to the same intermediate domain point. |
| mfdobj_x_tuning | A list created using get_mfd_df_real_time or get_mfd_list_real_time , denoting a list of functional data objects in the tuning data set (used to estimate control chart limits), each evolving up to an intermediate domain point, with observations of the multivariate functional covariates. The length of this list and <code>mod_list</code> must be equal, and their elements in the same position in the list must correspond to the same intermediate domain point. If NULL, the training data, i.e. the functional covariates in <code>mod_list</code> , are also used as the tuning data set. Default is NULL. |

| | |
|--------|---|
| alpha | See control_charts_sof_pc . |
| limits | See control_charts_sof_pc . |
| seed | Deprecated: see control_charts_sof_pc . |
| nfold | See control_charts_sof_pc . |
| ncores | If you want parallelization, give the number of cores/threads to be used when creating objects separately for different instants. |

Value

A list of data.frames each produced by [control_charts_sof_pc](#), corresponding to a given instant.

See Also

[sof_pc_real_time](#), [control_charts_sof_pc](#)

Examples

```
## Not run:
library(funcharts)
data("air")
air1 <- lapply(air, function(x) x[1:8, , drop = FALSE])
air2 <- lapply(air, function(x) x[9:10, , drop = FALSE])
mfdobj_x1_list <- get_mfd_list_real_time(air1[c("CO", "temperature")],
                                     n_basis = 15,
                                     lambda = 1e-2,
                                     k_seq = c(0.5, 1))
mfdobj_x2_list <- get_mfd_list_real_time(air2[c("CO", "temperature")],
                                     n_basis = 15,
                                     lambda = 1e-2,
                                     k_seq = c(0.5, 1))

y1 <- rowMeans(air1$NO2)
y2 <- rowMeans(air2$NO2)
mod_list <- sof_pc_real_time(y1, mfdobj_x1_list)
cclist <- control_charts_sof_pc_real_time(
  mod_list = mod_list,
  y_test = y2,
  mfdobj_x_test = mfdobj_x2_list)
plot_control_charts_real_time(cclist, 1)

## End(Not run)
```

| | |
|-----------|-----------------------------------|
| cont_plot | <i>Produce contribution plots</i> |
|-----------|-----------------------------------|

Description

This function produces a contribution plot from functional control charts for a given observation of a phase II data set, using `ggplot`.

Usage

```
cont_plot(cclist, id_num, which_plot = c("T2", "spe"), print_id = FALSE)
```

Arguments

| | |
|-------------------------|--|
| <code>cclist</code> | A data.frame produced by <code>control_charts_pca</code> , <code>control_charts_sof_pc</code> , <code>regr_cc_fof</code> , or <code>regr_cc_sof</code> . |
| <code>id_num</code> | An index number giving the observation in the phase II data set to be plotted, i.e. 1 for the first observation, 2 for the second, and so on. |
| <code>which_plot</code> | A character vector. Each value indicates which contribution you want to plot: "T2" indicates contribution to the Hotelling's T2 statistic, "spe" indicates contribution to the squared prediction error statistic. |
| <code>print_id</code> | A logical value, if TRUE, it prints also the id of the observation in the title of the <code>ggplot</code> . Default is FALSE. |

Value

A `ggplot` containing the contributions of functional variables to the monitoring statistics. Each plot is a bar plot, with bars corresponding to contribution values and horizontal black segments denoting corresponding (empirical) upper limits. Bars are coloured by red if contributions exceed their limit.

Examples

```
library(funcharts)
data("air")
air <- lapply(air, function(x) x[201:300, , drop = FALSE])
fun_covariates <- c("CO", "temperature")
mfdobj_x <- get_mfd_list(air[fun_covariates],
                       n_basis = 15,
                       lambda = 1e-2)

y <- rowMeans(air$NO2)
y1 <- y[1:60]
y_tuning <- y[61:90]
y2 <- y[91:100]
mfdobj_x1 <- mfdobj_x[1:60]
mfdobj_x_tuning <- mfdobj_x[61:90]
mfdobj_x2 <- mfdobj_x[91:100]
mod <- sof_pc(y1, mfdobj_x1)
```

```

cclist <- regr_cc_sof(object = mod,
                     y_new = y2,
                     mfdobj_x_new = mfdobj_x2,
                     y_tuning = y_tuning,
                     mfdobj_x_tuning = mfdobj_x_tuning,
                     include_covariates = TRUE)

get_ooc(cclist)
cont_plot(cclist, 3)

```

cor_mfd

Correlation Function for Multivariate Functional Data

Description

Computes the correlation function for two multivariate functional data objects of class `mfd`.

Usage

```
cor_mfd(mfdobj1, mfdobj2 = mfdobj1)
```

Arguments

`mfdobj1` An object of class `mfd` representing the first multivariate functional data set. It contains N observations of a p -dimensional multivariate functional variable.

`mfdobj2` An object of class `mfd` representing the second multivariate functional data set. Defaults to `mfdobj1`. If provided, it must also contain N observations of a p -dimensional multivariate functional variable.

Details

The function calculates the correlation between all pairs of dimensions from the two multivariate functional data objects. The data is first scaled using `scale_mfd`, and the correlation is then computed as the covariance of the scaled data using `cov_mfd`.

Value

A `bifd` object representing the correlation function of the two input objects. The output is a collection of p^2 functional surfaces, each corresponding to the correlation between two components of the multivariate functional data.

Examples

```

## Not run:
library(funcharts)
data("air")
x <- get_mfd_list(air[1:3])
cor_result <- cor_mfd(x)

```

```
plot_bifd(cov_result)

## End(Not run)
```

 cov_mfd

Covariance Function for Multivariate Functional Data

Description

Computes the covariance function for two multivariate functional data objects of class `mfd`.

Usage

```
cov_mfd(mfdobj1, mfdobj2 = mfdobj1)
```

Arguments

| | |
|----------------------|---|
| <code>mfdobj1</code> | An object of class <code>mfd</code> representing the first multivariate functional data set. It contains N observations of a p -dimensional multivariate functional variable. |
| <code>mfdobj2</code> | An object of class <code>mfd</code> representing the second multivariate functional data set. Defaults to <code>mfdobj1</code> . If provided, it must also contain N observations of a p -dimensional multivariate functional variable. |

Details

The function calculates the covariance between all pairs of dimensions from the two multivariate functional data objects. Each covariance is represented as a functional surface in the resulting `bifd` object. The covariance function is useful for analyzing relationships between functional variables.

Value

A `bifd` object representing the covariance function of the two input objects. The output is a collection of p^2 functional surfaces, each corresponding to the covariance between two components of the multivariate functional data.

Examples

```
## Not run:
library(funcharts)
data("air")
x <- get_mfd_list(air[1:3])
cov_result <- cov_mfd(x)
plot_bifd(cov_result)

## End(Not run)
```

| | |
|--------------|--|
| data_sim_mfd | <i>Simulate multivariate functional data</i> |
|--------------|--|

Description

Simulate random coefficients and create a multivariate functional data object of class `mfd`. It is mainly for internal use, to check that the package functions work.

Usage

```
data_sim_mfd(nobs = 5, nbasis = 5, nvar = 2, seed)
```

Arguments

| | |
|---------------------|--|
| <code>nobs</code> | Number of functional observations to be simulated. |
| <code>nbasis</code> | Number of basis functions. |
| <code>nvar</code> | Number of functional covariates. |
| <code>seed</code> | Deprecated: use <code>set.seed()</code> before calling the function for reproducibility. |

Value

A simulated object of class `mfd`.

Examples

```
library(funcharts)
data_sim_mfd()
```

| | |
|--------|---|
| fof_pc | <i>Function-on-function linear regression based on principal components</i> |
|--------|---|

Description

Function-on-function linear regression based on principal components. This function performs multivariate functional principal component analysis (MFPCA) to extract multivariate functional principal components from the multivariate functional covariates as well as from the functional response, then it builds a linear regression model of the response scores on the covariate scores. Both functional covariates and response are standardized before the regression. See Centofanti et al. (2021) for additional details.

Usage

```
fof_pc(
  mfdobj_y,
  mfdobj_x,
  tot_variance_explained_x = 0.95,
  tot_variance_explained_y = 0.95,
  tot_variance_explained_res = 0.95,
  components_x = NULL,
  components_y = NULL,
  type_residuals = "standard"
)
```

Arguments

| | |
|----------------------------|---|
| mfdobj_y | A multivariate functional data object of class <code>mfd</code> denoting the functional response variable. Although it is a multivariate functional data object, it must have only one functional variable. |
| mfdobj_x | A multivariate functional data object of class <code>mfd</code> denoting the functional covariates. |
| tot_variance_explained_x | The minimum fraction of variance that has to be explained by the multivariate functional principal components retained into the MFPCA model fitted on the functional covariates. Default is 0.95. |
| tot_variance_explained_y | The minimum fraction of variance that has to be explained by the multivariate functional principal components retained into the MFPCA model fitted on the functional response. Default is 0.95. |
| tot_variance_explained_res | The minimum fraction of variance that has to be explained by the multivariate functional principal components retained into the MFPCA model fitted on the functional residuals of the functional regression model. Default is 0.95. |
| components_x | A vector of integers with the components over which to project the functional covariates. If <code>NULL</code> , the first components that explain a minimum fraction of variance equal to <code>tot_variance_explained_x</code> is selected. #' If this is not <code>NULL</code> , the criteria to select components are ignored. Default is <code>NULL</code> . |
| components_y | A vector of integers with the components over which to project the functional response. If <code>NULL</code> , the first components that explain a minimum fraction of variance equal to <code>tot_variance_explained_y</code> is selected. #' If this is not <code>NULL</code> , the criteria to select components are ignored. Default is <code>NULL</code> . |
| type_residuals | A character value that can be "standard" or "studentized". If "standard", the MFPCA on functional residuals is calculated on the standardized covariates and response. If "studentized", the MFPCA on studentized version of the functional residuals is calculated on the non-standardized covariates and response. See Centofanti et al. (2021) for additional details. |

Value

A list containing the following arguments:

- `mod`: an object of class `lm` that is a linear regression model where the response variables are the MFPCA scores of the response variable and the covariates are the MFPCA scores of the functional covariates. `mod$coefficients` contains the matrix of coefficients of the functional regression basis functions,
- `beta_fd`: a `bifd` object containing the bivariate functional regression coefficients $\beta(s, t)$ estimated with the function-on-function linear regression model,
- `fitted.values`: a multivariate functional data object of class `mfd` with the fitted values of the functional response observations based on the function-on-function linear regression model,
- `residuals_original_scale`: a multivariate functional data object of class `mfd` with the functional residuals of the function-on-function linear regression model on the original scale, i.e. they are the difference between `mfdobj_y` and `fitted.values`,
- `residuals`: a multivariate functional data object of class `mfd` with the functional residuals of the function-on-function linear regression model, standardized or studentized depending on the argument `type_residuals`,
- `type_residuals`: the same as the provided argument,
- `pca_x`: an object of class `pca_mfd` obtained by doing MFPCA on the functional covariates,
- `pca_y`: an object of class `pca_mfd` obtained by doing MFPCA on the functional response,
- `pca_res`: an object of class `pca_mfd` obtained by doing MFPCA on the functional residuals,
- `components_x`: a vector of integers with the components selected in the `pca_x` model,
- `components_y`: a vector of integers with the components selected in the `pca_y` model,
- `components_res`: a vector of integers with the components selected in the `pca_res` model,
- `y_standardized`: the standardized functional response obtained doing `scale_mfd(mfdobj_y)`,
- `tot_variance_explained_x`: the same as the provided argument
- `tot_variance_explained_y`: the same as the provided argument
- `tot_variance_explained_res`: the same as the provided argument
- `get_studentized_residuals`: a function that allows to calculate studentized residuals on new data, given the estimated function-on-function linear regression model.

Author(s)

C. Capezza, F. Centofanti

References

Centofanti F, Lepore A, Menafoglio A, Palumbo B, Vantini S. (2021) Functional Regression Control Chart. *Technometrics*, 63(3), 281–294. doi:[10.1080/00401706.2020.1753581](https://doi.org/10.1080/00401706.2020.1753581)

Examples

```
library(funcharts)
data("air")
air <- lapply(air, function(x) x[1:10, , drop = FALSE])
fun_covariates <- c("CO", "temperature")
mfdobj <- get_mfd_list(air, lambda = 1e-2)
mfdobj_y <- mfdobj[, "NO2"]
```

```
mfdobj_x <- mfdobj[, fun_covariates]
mod <- fof_pc(mfdobj_y, mfdobj_x)
```

| | |
|------------------|---|
| fof_pc_real_time | <i>Get a list of function-on-function linear regression models estimated on functional data each evolving up to an intermediate domain point.</i> |
|------------------|---|

Description

This function produces a list of objects, each of them contains the result of applying `fof_pc` to a functional response variable and multivariate functional covariates evolved up to an intermediate domain point.

Usage

```
fof_pc_real_time(
  mfdobj_y_list,
  mfdobj_x_list,
  tot_variance_explained_x = 0.95,
  tot_variance_explained_y = 0.95,
  tot_variance_explained_res = 0.95,
  components_x = NULL,
  components_y = NULL,
  type_residuals = "standard",
  ncores = 1
)
```

Arguments

| | |
|---|--|
| <code>mfdobj_y_list</code> | A list created using <code>get_mfd_df_real_time</code> or <code>get_mfd_list_real_time</code> , denoting a list of functional data objects, each evolving up to an intermediate domain point, with observations of the functional response variable. |
| <code>mfdobj_x_list</code> | A list created using <code>get_mfd_df_real_time</code> or <code>get_mfd_list_real_time</code> , denoting a list of functional data objects, each evolving up to an intermediate domain point, with observations of the multivariate functional covariates. |
| <code>tot_variance_explained_x</code> | See <code>fof_pc</code> . |
| <code>tot_variance_explained_y</code> | See <code>fof_pc</code> . |
| <code>tot_variance_explained_res</code> | See <code>fof_pc</code> . |
| <code>components_x</code> | See <code>fof_pc</code> . |
| <code>components_y</code> | See <code>fof_pc</code> . |
| <code>type_residuals</code> | See <code>fof_pc</code> . |
| <code>ncores</code> | If you want parallelization, give the number of cores/threads to be used when creating objects separately for different instants. |

Value

A list of lists each produced by `fof_pc`, corresponding to a given instant.

Author(s)

C. Capezza, F. Centofanti

See Also

[fof_pc](#), [get_mfd_df_real_time](#), [get_mfd_list_real_time](#)

Examples

```
library(funcharts)
data("air")
air <- lapply(air, function(x) x[1:10, , drop = FALSE])
mfdoobj_y_list <- get_mfd_list_real_time(air["NO2"],
                                       n_basis = 15,
                                       lambda = 1e-2,
                                       k_seq = c(0.5, 0.75, 1))
mfdoobj_x_list <- get_mfd_list_real_time(air[c("CO", "temperature")],
                                       n_basis = 15,
                                       lambda = 1e-2,
                                       k_seq = c(0.5, 0.75, 1))
mod_list <- fof_pc_real_time(mfdoobj_y_list, mfdoobj_x_list)
```

FRTM_PhaseI

Phase I of the FRTM method.

Description

This function implements the design phase (Phase I) of FRTM method.

Usage

```
FRTM_PhaseI(
  data_tra,
  data_tun = NULL,
  alpha = 0.05,
  n_basis_xall = 30,
  control.FDTW = list(),
  control.mFPCA = list(),
  control.rtr = list(),
  ncores = 1,
  print = TRUE
)
```

Arguments

| | |
|----------------------------|---|
| <code>data_tra</code> | A list containing the following arguments: <code>x_err</code> a list containing the discrete observations for each curve of the training set; <code>grid_i</code> a list of vector of time points where the curves of the training set are sampled. |
| <code>data_tun</code> | A list containing the following arguments: <code>grid_i</code> a list containing the discrete observations for each curve of the tuning set; <code>grid_i</code> a list of vector of time points where the curves of the tuning set are sampled. If NULL, the tuning set is not used. |
| <code>alpha</code> | Overall type I error probability to obtain the control chart limits. |
| <code>n_basis_xall</code> | Number of basis to obtain the functional observation via the spline smoothing approach based on cubic B-splines and a roughness penalty on the second derivative. |
| <code>control.FDTW</code> | A list of control parameters for the open-end/open-begin functional dynamic time warping to replace defaults returned by <code>par.FDTW</code> . Values not set assume default values. |
| <code>control.mFPCA</code> | A list of control parameters for the mixed functional principal component analysis to replace defaults returned by <code>par.mFPCA</code> . Values not set assume default values. |
| <code>control.rtr</code> | A list of control parameters for the real-time registration step to replace defaults returned by <code>par.rtr</code> . Values not set assume default values. |
| <code>ncores</code> | If <code>ncores>1</code> , then parallel computing is used, with <code>ncores</code> cores. Default is 1. |
| <code>print</code> | If TRUE, some information are printed. Default is TRUE. |

Value

A list containing the following arguments:

`T2_fd` List of T^2 functions for each observation in the tuning set.

`SPE_fd` List of SPE functions for each observation in the tuning set.

`CL_T2` Control limit of the Hotelling's T^2 control chart.

`CL_SPE` Control limit of the SPE control chart.

`template_fd` Template function used in the registration.

`der_template_fd` First derivative of the template function.

`u_fd` Upper extreme of the band constraint.

`l_fd` Lower extreme of the band constraint.

`x_list_tun` List, for each observation in the tuning set, of partial registered functions.

`h_list_tun` List, for each observation in the tuning set, of partial warping functions.

`x_list` List, for each observation in the training set, of partial registered functions.

`h_list` List, for each observation in the training set, of partial warping functions.

`x_err` A list containing the discrete observations for each curve of the training set.

`grid_i` A list of vector of time points where the curves of the training set are sampled.

`x_list_smooth` Smooth curves from the training set.

lambda Lambda identified through the average curve distance to obtain the OEB-FDTW solution.
 par_reg Additional parameters to be used in the monitoring phase (Phase II).

Author(s)

F. Centofanti

References

Centofanti, F., A. Lepore, M. Kulahci, and M. P. Spooner (2024). Real-time monitoring of functional data. Accepted for publication in *Journal of Quality Technology*.

See Also

[FRTM_PhaseI](#)

Examples

```
library(funcharts)
data <- simulate_data_FRTM(n_obs = 20)

data_oc <-
  simulate_data_FRTM(
    n_obs = 2,
    scenario = "1",
    shift = "0C_h",
    severity = 0.5
  )

lambda <- 10 ^ -5
max_x <- max(unlist(data$grid_i))
seq_t_tot <- seq(0, 1, length.out = 30)[-1]
seq_x <- seq(0.1, max_x, length.out = 10)

## Not run:
mod_phaseI_FRTM <- FRTM_PhaseI(
  data_tra = data,
  control.FDTW = list(
    M = 30,
    N = 30,
    lambda = lambda,
    seq_t = seq_t_tot,
    iter_tem = 1,
    iter = 1
  ),
  control.rtr = list(seq_x = seq_x)
)
mod_phaseII_FRTM <- FRTM_PhaseII(data_oc = data_oc , mod_phaseI = mod_phaseI_FRTM)

plot(mod_phaseI_FRTM)
plot(mod_phaseII_FRTM)
```

```
## End(Not run)
```

FRTM_PhaseII *Phase II of the FRTM method.*

Description

This function implements the monitoring phase (Phase II) of FRTM method.

Usage

```
FRTM_PhaseII(data_oc, mod_phaseI, ncores = 1)
```

Arguments

| | |
|------------|---|
| data_oc | A list containing the following arguments: x_err a list containing the discrete observations for each curve to be monitored; grid_i a list of vector of time points where the curves to be monitored are sampled. |
| mod_phaseI | An object of class mod_phaseI_FRTM obtained as output of the function FRTM_PhaseI. |
| ncores | If ncores>1, then parallel computing is used, with ncores cores. Default is 1. |

Value

A list containing the following arguments:

- T2_fd List of T^2 functions for each observation.
- SPE_fd List of SPE functions for each observation.
- CL_T2 Control limit of the Hotelling's T^2 control chart.
- CL_SPE Control limit of the SPE control chart.
- x_err A list containing the discrete observations for each curve.
- grid_i A list of vector of time points where the curves are sampled.
- x_list_smooth Smooth curves.
- mod_phaseI An object of class mod_phaseI_FRTM obtained as output of the function FRTM_PhaseI.

Author(s)

F. Centofanti

References

Centofanti, F., A. Lepore, M. Kulahci, and M. P. Spooner (2024). Real-time monitoring of functional data. Accepted for publication in *Journal of Quality Technology*.

Examples

```
library(funcharts)
data <- simulate_data_FRTM(n_obs = 20)

data_oc <-
  simulate_data_FRTM(
    n_obs = 2,
    scenario = "1",
    shift = "0C_h",
    severity = 0.5
  )

lambda <- 10 ^ -5
max_x <- max(unlist(data$grid_i))
seq_t_tot <- seq(0, 1, length.out = 30)[-1]
seq_x <- seq(0.1, max_x, length.out = 10)

## Not run:
mod_phaseI_FRTM <- FRTM_PhaseI(
  data_tra = data,
  control.FDTW = list(
    M = 30,
    N = 30,
    lambda = lambda,
    seq_t = seq_t_tot,
    iter_tem = 1,
    iter = 1
  ),
  control.rtr = list(seq_x = seq_x)
)
mod_phaseII_FRTM <- FRTM_PhaseII(data_oc = data_oc , mod_phaseI = mod_phaseI_FRTM)

plot(mod_phaseI_FRTM)
plot(mod_phaseII_FRTM)

## End(Not run)
```

functional_filter *Finds functional componentwise outliers*

Description

It finds functional componentwise outliers as described in Capezza et al. (2024).

Usage

```
functional_filter(
```

```

mfdobj,
method_pca = "ROBPCA",
alpha = 0.95,
fev = 0.999,
delta = 0.1,
alpha_binom = 0.99,
bivariate = TRUE,
max_proportion_componentwise = 0.5
)

```

Arguments

| | |
|------------------------------|---|
| mfdobj | A multivariate functional data object of class <code>mfd</code> . |
| method_pca | The method used in <code>rpca_mfd</code> to perform robust multivariate functional principal component analysis (RoMFPCA). See rpca_mfd . |
| alpha | Probability value such that only values of functional distances greater than the alpha-quantile of the Chi-squared distribution, with a number of degrees of freedom equal to the number of principal components selected by <code>fev</code> , are considered to determine the proportion of flagged componentwise outliers. Default value is 0.95, as recommended by Agostinelli et al. (2015). See Capezza et al. (2024) for more details. |
| fev | Number between 0 and 1 denoting the fraction of variability that must be explained by the principal components to be selected to calculate functional distances after applying RoMFPCA on <code>mfdobj</code> . Default is 0.999. |
| delta | Number between 0 and 1 denoting the parameter of the Binomial distribution whose <code>alpha_binom</code> -quantile determines the threshold used in the bivariate filter. Given the <i>i</i> -th observation and the <i>j</i> -th functional variable, the number of pairs flagged as functional componentwise outliers in the <i>i</i> -th observation where the component (<i>i</i> , <i>j</i>) is involved is compared against this threshold to identify additional functional componentwise outliers to the ones found by the univariate filter. Default is 0.1, recommended as conservative choice by Leung et al. (2017). See Capezza et al. (2024) for more details. |
| alpha_binom | Probability value such that the alpha-quantile of the Binomial distribution is considered as threshold in the bivariate filter. See <code>delta</code> and Capezza et al. (2024) for more details. Default value is 0.99. |
| bivariate | If TRUE, both univariate and bivariate filters are applied. If FALSE, only the univariate filter is used. Default is TRUE. |
| max_proportion_componentwise | If the functional filter identifies a proportion of functional componentwise outliers larger than <code>max_proportion_componentwise</code> , for a given observation, then it is considered as a functional casewise outlier. Default value is 0.5. |

Value

A list with two elements. The first element is an `mfd` object containing the original observation in the `mfdobj` input, but where the basis coefficients of the components identified as functional componentwise outliers are replaced by NA. The second element of the list is a list of numbers,

with length equal to the number of functional variables in `mfdobj`. Each element of this list contains the observations of the flagged functional componentwise outliers for the corresponding functional variable.

Author(s)

C. Capezza, F. Centofanti

References

- Agostinelli, C., Leung, A., Yohai, V. J., and Zamar, R. H. (2015). Robust estimation of multivariate location and scatter in the presence of cellwise and casewise contamination. *Test*, 24(3):441–461.
- Capezza, C., Centofanti, F., Lepore, A., Palumbo, B. (2024) Robust Multivariate Functional Control Charts. *Technometrics*, 66(4):531–547, doi:10.1080/00401706.2024.2327346.
- Leung, A., Yohai, V., and Zamar, R. (2017). Multivariate location and scatter matrix estimation under cellwise and casewise contamination. *Computational Statistics & Data Analysis*, 111:59–76.

Examples

```
## Not run:
library(funcharts)
mfdobj <- get_mfd_list(air, grid = 1:24, n_basis = 13, lambda = 1e-2)
plot_mfd(mfdobj)
out <- functional_filter(mfdobj)

## End(Not run)
```

get_mfd_array

Get Multivariate Functional Data from a three-dimensional array

Description

Get Multivariate Functional Data from a three-dimensional array

Usage

```
get_mfd_array(
  data_array,
  grid = NULL,
  n_basis = 30,
  n_order = 4,
  basisobj = NULL,
  Lfdobj = 2,
  lambda = NULL,
  lambda_grid = 10^seq(-10, 1, length.out = 10),
  ncores = 1
)
```

Arguments

| | |
|-------------|--|
| data_array | A three-dimensional array. The first dimension corresponds to argument values, the second to replications, and the third to variables within replications. |
| grid | See get_mfd_list . |
| n_basis | See get_mfd_list . |
| n_order | #' See get_mfd_list . |
| basisobj | #' See get_mfd_list . |
| Lfdobj | #' See get_mfd_list . |
| lambda | See get_mfd_list . |
| lambda_grid | See get_mfd_list . |
| ncores | Deprecated. See get_mfd_list . |

Value

An object of class `mfd`. See also `?mfd` for additional details on the multivariate functional data class.

See Also

[get_mfd_list](#), [get_mfd_df](#)

Examples

```
library(funcharts)
library(fda)
data("CanadianWeather")
mfdobj <- get_mfd_array(CanadianWeather$dailyAv[, 1:10, ],
                      lambda = 1e-5)

plot_mfd(mfdobj)
```

get_mfd_array_real_time

Get a list of functional data objects each evolving up to an intermediate domain point.

Description

This function produces a list functional data objects, each evolving up to an intermediate domain point, that can be used to estimate models that allow real-time predictions of incomplete functions, from the current functional domain up to the end of the observation, and to build control charts for real-time monitoring.

It calls the function [get_mfd_array](#) for each domain point.

Usage

```

get_mfd_array_real_time(
  data_array,
  grid = NULL,
  n_basis = 30,
  n_order = 4,
  basisobj = NULL,
  Lfdobj = 2,
  lambda = NULL,
  lambda_grid = 10^seq(-10, 1, length.out = 10),
  k_seq = seq(from = 0.25, to = 1, length.out = 10),
  ncores = 1
)

```

Arguments

| | |
|-------------|---|
| data_array | See get_mfd_array . |
| grid | See get_mfd_array . |
| n_basis | See get_mfd_array . |
| n_order | See get_mfd_array . |
| basisobj | See get_mfd_array . |
| Lfdobj | See get_mfd_array . |
| lambda | See get_mfd_array . |
| lambda_grid | See get_mfd_array . |
| k_seq | A vector of values between 0 and 1, containing the domain points over which functional data are to be evaluated in real time. If the domain is the interval (a,b), for each instant k in the sequence, functions are evaluated in (a,k(b-a)). |
| ncores | If you want parallelization, give the number of cores/threads to be used when creating mfd objects separately for different instants. |

Value

A list of mfd objects as produced by [get_mfd_array](#).

See Also

[get_mfd_array](#)

Examples

```

library(funcharts)
library(fda)
data("CanadianWeather")
fdobj <- get_mfd_array_real_time(CanadianWeather$dailyAv[, 1:5, 1:2],
                                lambda = 1e-2)

```

get_mfd_df

*Get Multivariate Functional Data from a data frame***Description**

Get Multivariate Functional Data from a data frame

Usage

```
get_mfd_df(
  dt,
  domain,
  arg,
  id,
  variables,
  n_basis = 30,
  n_order = 4,
  basisobj = NULL,
  Lfdobj = 2,
  lambda = NULL,
  lambda_grid = 10^seq(-10, 1, length.out = 10),
  ncores = 1
)
```

Arguments

| | |
|-----------|--|
| dt | A data frame containing the discrete data. For each functional variable, a single column, whose name is provided in the argument <code>variables</code> , contains discrete values of that variable for all functional observation. The column indicated by the argument <code>id</code> denotes which is the functional observation in each row. The column indicated by the argument <code>arg</code> gives the argument value at which the discrete values of the functional variables are observed for each row. |
| domain | A numeric vector of length 2 defining the interval over which the functional data object can be evaluated. |
| arg | A character variable, which is the name of the column of the data frame <code>dt</code> giving the argument values at which the functional variables are evaluated for each row. |
| id | A character variable indicating which is the functional observation in each row. |
| variables | A vector of characters of the column names of the data frame <code>dt</code> indicating the functional variables. |
| n_basis | An integer variable specifying the number of basis functions; default value is 30. See details on basis functions. |
| n_order | An integer specifying the order of b-splines, which is one higher than their degree. The default of 4 gives cubic splines. |

| | |
|-------------|---|
| basisobj | An object of class <code>basisfd</code> defining the basis function expansion. Default is <code>NULL</code> , which means that a <code>basisfd</code> object is created by doing <code>create.bspline.basis(rangeval = domain, nbasis = n_basis, norder = n_order)</code> |
| Lfdobj | An object of class <code>Lfd</code> defining a linear differential operator of order <code>m</code> . It is used to specify a roughness penalty through <code>fdPar</code> . Alternatively, a nonnegative integer specifying the order <code>m</code> can be given and is passed as <code>Lfdobj</code> argument to the function <code>fdPar</code> , which indicates that the derivative of order <code>m</code> is penalized. Default value is 2, which means that the integrated squared second derivative is penalized. |
| lambda | A non-negative real number. If you want to use a single specified smoothing parameter for all functional data objects in the dataset, this argument is passed to the function <code>fda::fdPar</code> . Default value is <code>NULL</code> , in this case the smoothing parameter is chosen by minimizing the generalized cross-validation (GCV) criterion over the grid of values given by the argument. See details on how smoothing parameters work. |
| lambda_grid | A vector of non-negative real numbers. If <code>lambda</code> is provided as a single number, this argument is ignored. If <code>lambda</code> is <code>NULL</code> , then this provides the grid of values over which the optimal smoothing parameter is searched. Default value is <code>10^seq(-10, 1, l=20)</code> . |
| ncores | If you want parallelization, give the number of cores/threads to be used when doing GCV separately on all observations. |

Details

Basis functions are created with `fda::create.bspline.basis(domain, n_basis)`, i.e. B-spline basis functions of order 4 with equally spaced knots are used to create `mfd` objects.

The smoothing penalty `lambda` is provided as `fda::fdPar(bs, 2, lambda)`, where `bs` is the basis object and 2 indicates that the integrated squared second derivative is penalized.

Rather than having a data frame with long format, i.e. with all functional observations in a single column for each functional variable, if all functional observations are observed on a common equally spaced grid, discrete data may be available in matrix form for each functional variable. In this case, see `get_mfd_list`.

Value

An object of class `mfd`. See also `?mfd` for additional details on the multivariate functional data class.

See Also

[get_mfd_list](#)

Examples

```
library(funcharts)

x <- seq(1, 10, length = 25)
y11 <- cos(x)
y21 <- cos(2 * x)
```

```

y12 <- sin(x)
y22 <- sin(2 * x)
df <- data.frame(id = factor(rep(1:2, each = length(x))),
                 x = rep(x, times = 2),
                 y1 = c(y11, y21),
                 y2 = c(y12, y22))

mfdobj <- get_mfd_df(dt = df,
                    domain = c(1, 10),
                    arg = "x",
                    id = "id",
                    variables = c("y1", "y2"),
                    lambda = 1e-5)

```

`get_mfd_df_real_time` *Get a list of functional data objects each evolving up to an intermediate domain point.*

Description

This function produces a list functional data objects, each evolving up to an intermediate domain point, that can be used to estimate models that allow real-time predictions of incomplete functions, from the current functional domain up to the end of the observation, and to build control charts for real-time monitoring.

It calls the function `get_mfd_df` for each domain point.

Usage

```

get_mfd_df_real_time(
  dt,
  domain,
  arg,
  id,
  variables,
  n_basis = 30,
  n_order = 4,
  basisobj = NULL,
  Lfdobj = 2,
  lambda = NULL,
  lambda_grid = 10^seq(-10, 1, length.out = 10),
  k_seq = seq(from = 0.25, to = 1, length.out = 10),
  ncores = 1
)

```

Arguments

| | |
|-------------|---|
| dt | See get_mfd_df . |
| domain | See get_mfd_df . |
| arg | See get_mfd_df . |
| id | See get_mfd_df . |
| variables | See get_mfd_df . |
| n_basis | See get_mfd_df . |
| n_order | See get_mfd_df . |
| basisobj | See get_mfd_df . |
| Lfdobj | See get_mfd_df . |
| lambda | See get_mfd_df . |
| lambda_grid | See get_mfd_df . |
| k_seq | A vector of values between 0 and 1, containing the domain points over which functional data are to be evaluated in real time. If the domain is the interval (a,b), for each instant k in the sequence, functions are evaluated in (a,k(b-a)). |
| ncores | If you want parallelization, give the number of cores/threads to be used when creating mfd objects separately for different instants. |

Value

A list of mfd objects as produced by [get_mfd_df](#), corresponding to a given instant.

See Also

[get_mfd_df](#)

Examples

```
library(funcharts)

x <- seq(1, 10, length = 25)
y11 <- cos(x)
y21 <- cos(2 * x)
y12 <- sin(x)
y22 <- sin(2 * x)
df <- data.frame(id = factor(rep(1:2, each = length(x))),
                 x = rep(x, times = 2),
                 y1 = c(y11, y21),
                 y2 = c(y12, y22))

mfdobj_list <- get_mfd_df_real_time(dt = df,
                                   domain = c(1, 10),
                                   arg = "x",
                                   id = "id",
                                   variables = c("y1", "y2"),
                                   lambda = 1e-2)
```

| | |
|------------|--|
| get_mfd_fd | <i>Convert a fd object into a Multivariate Functional Data object.</i> |
|------------|--|

Description

Convert a fd object into a Multivariate Functional Data object.

Usage

```
get_mfd_fd(fdobj)
```

Arguments

fdobj An object of class fd.

Value

An object of class mfd. See also ?mfd for additional details on the multivariate functional data class.

See Also

mfd

Examples

```
library(funcharts)
library(fda)
bs <- create.bspline.basis(nbasis = 10)
fdobj <- fd(coef = 1:10, basisobj = bs)
mfdobj <- get_mfd_fd(fdobj)
```

| | |
|--------------|---|
| get_mfd_list | <i>Get Multivariate Functional Data from a list of matrices</i> |
|--------------|---|

Description

Get Multivariate Functional Data from a list of matrices

Usage

```

get_mfd_list(
  data_list,
  grid = NULL,
  n_basis = 30,
  n_order = 4,
  basisobj = NULL,
  Lfdobj = 2,
  lambda = NULL,
  lambda_grid = 10^seq(-10, 1, length.out = 10),
  ncores = 1
)

```

Arguments

| | |
|--------------------------|--|
| <code>data_list</code> | A named list of matrices. Names of the elements in the list denote the functional variable names. Each matrix in the list corresponds to a functional variable. All matrices must have the same dimension, where the number of rows corresponds to replications, while the number of columns corresponds to the argument values at which functions are evaluated. |
| <code>grid</code> | A numeric vector, containing the argument values at which functions are evaluated. Its length must be equal to the number of columns in each matrix in <code>data_list</code> . Default is <code>NULL</code> , in this case a vector equally spaced numbers between 0 and 1 is created, with as many numbers as the number of columns in each matrix in <code>data_list</code> . |
| <code>n_basis</code> | An integer variable specifying the number of basis functions; default value is 30. See details on basis functions. |
| <code>n_order</code> | An integer specifying the order of B-splines, which is one higher than their degree. The default of 4 gives cubic splines. |
| <code>basisobj</code> | An object of class <code>basisfd</code> defining the B-spline basis function expansion. Default is <code>NULL</code> , which means that a <code>basisfd</code> object is created by doing <code>create.bspline.basis(rangeval = domain, nbasis = n_basis, norder = n_order)</code> |
| <code>Lfdobj</code> | An object of class <code>Lfd</code> defining a linear differential operator of order m . It is used to specify a roughness penalty through <code>fdPar</code> . Alternatively, a nonnegative integer specifying the order m can be given and is passed as <code>Lfdobj</code> argument to the function <code>fdPar</code> , which indicates that the derivative of order m is penalized. Default value is 2, which means that the integrated squared second derivative is penalized. |
| <code>lambda</code> | A non-negative real number. If you want to use a single specified smoothing parameter for all functional data objects in the dataset, this argument is passed to the function <code>fda::fdPar</code> . Default value is <code>NULL</code> , in this case the smoothing parameter is chosen by minimizing the generalized cross-validation (GCV) criterion over the grid of values given by the argument. See details on how smoothing parameters work. |
| <code>lambda_grid</code> | A vector of non-negative real numbers. If <code>lambda</code> is provided as a single number, this argument is ignored. If <code>lambda</code> is <code>NULL</code> , then this provides the grid of |

values over which the optimal smoothing parameter is searched. Default value is $10^{\text{seq}(-10, 1, l=20)}$.

ncores Deprecated.

Details

Basis functions are created with `fda::create.bspline.basis(domain, n_basis)`, i.e. B-spline basis functions of order 4 with equally spaced knots are used to create mfd objects.

The smoothing penalty λ is provided as `fda::fdPar(bs, 2, lambda)`, where `bs` is the basis object and 2 indicates that the integrated squared second derivative is penalized.

Rather than having a list of matrices, you may have a data frame with long format, i.e. with all functional observations in a single column for each functional variable. In this case, see `get_mfd_df`.

Value

An object of class `mfd`. See also `mfd` for additional details on the multivariate functional data class.

See Also

[mfd](#), [get_mfd_list](#), [get_mfd_array](#)

Examples

```
library(funcharts)
data("air")
# Only take first 5 multivariate functional observations
# and only two variables from air
air_small <- lapply(air[c("NO2", "CO")], function(x) x[1:5, ])
mfobj <- get_mfd_list(data_list = air_small)
```

get_mfd_list_real_time

Get a list of functional data objects each evolving up to an intermediate domain point.

Description

This function produces a list functional data objects, each evolving up to an intermediate domain point, that can be used to estimate models that allow real-time predictions of incomplete functions, from the current functional domain up to the end of the observation, and to build control charts for real-time monitoring.

It calls the function `get_mfd_list` for each domain point.

Usage

```
get_mfd_list_real_time(
  data_list,
  grid = NULL,
  n_basis = 30,
  n_order = 4,
  basisobj = NULL,
  Lfdobj = 2,
  lambda = NULL,
  lambda_grid = 10^seq(-10, 1, length.out = 10),
  k_seq = seq(from = 0.2, to = 1, by = 0.1),
  ncores = 1
)
```

Arguments

| | |
|-------------|---|
| data_list | See get_mfd_list . |
| grid | See get_mfd_list . |
| n_basis | See get_mfd_list . |
| n_order | See get_mfd_list . |
| basisobj | See get_mfd_list . |
| Lfdobj | See get_mfd_list . |
| lambda | See get_mfd_list . |
| lambda_grid | See get_mfd_df . |
| k_seq | A vector of values between 0 and 1, containing the domain points over which functional data are to be evaluated in real time. If the domain is the interval (a,b), for each instant k in the sequence, functions are evaluated in (a,a+k(b-a)). |
| ncores | If you want parallelization, give the number of cores/threads to be used when creating mfd objects separately for different instants. |

Value

A list of mfd objects as produced by [get_mfd_list](#).

See Also

[get_mfd_list](#)

Examples

```
library(funcharts)
data("air")
# Only take first 5 multivariate functional observations from air
air_small <- lapply(air, function(x) x[1:5, ])
# Consider only 3 domain points: 0.5, 0.75, 1
mfdobj <- get_mfd_list_real_time(data_list = air_small,
                                lambda = 1e-2,
```

```
k_seq = c(0.5, 0.75, 1))
```

```
get_ooc
```

Get out of control observations from control charts

Description

Get out of control observations from control charts

Usage

```
get_ooc(cclist)
```

Arguments

`cclist` A data.frame produced by [control_charts_pca](#), [control_charts_sof_pc](#), [regr_cc_fof](#), or [regr_cc_sof](#).

Value

A data.frame with the same number of rows as `cclist`, and the same number of columns apart from the columns indicating control chart limits. Each value is TRUE if the corresponding observation is in control and FALSE otherwise.

Examples

```
library(funcharts)
data("air")
air <- lapply(air, function(x) x[201:300, , drop = FALSE])
fun_covariates <- c("CO", "temperature")
mfdoobj_x <- get_mfd_list(air[fun_covariates],
                        n_basis = 15,
                        lambda = 1e-2)

y <- rowMeans(air$NO2)
y1 <- y[1:60]
y_tuning <- y[61:90]
y2 <- y[91:100]
mfdoobj_x1 <- mfdoobj_x[1:60]
mfdoobj_x_tuning <- mfdoobj_x[61:90]
mfdoobj_x2 <- mfdoobj_x[91:100]
mod <- sof_pc(y1, mfdoobj_x1)
cclist <- regr_cc_sof(object = mod,
                    y_new = y2,
                    mfdoobj_x_new = mfdoobj_x2,
                    y_tuning = y_tuning,
                    mfdoobj_x_tuning = mfdoobj_x_tuning,
                    include_covariates = TRUE)

get_ooc(cclist)
```

| | |
|------------------|---|
| get_outliers_mfd | <i>Get outliers from multivariate functional data</i> |
|------------------|---|

Description

Get outliers from multivariate functional data using the functional boxplot with the modified band depth of Sun et al. (2011, 2012). This function relies on the fbplot function of the roahd package.

Usage

```
get_outliers_mfd(mfdobj)
```

Arguments

mfdobj A multivariate functional data object of class mfd

Value

A numeric vector with the indexes of the functional observations signaled as outliers.

References

- Sun, Y., & Genton, M. G. (2011). Functional boxplots. *Journal of Computational and Graphical Statistics*, 20(2), 316-334.
- Sun, Y., & Genton, M. G. (2012). Adjusted functional boxplots for spatio-temporal data visualization and outlier detection. *Environmetrics*, 23(1), 54-64.

Examples

```
library(funcharts)
data("air")
air <- lapply(air, function(x) x[1:20], , drop = FALSE])
fun_covariates <- c("CO", "temperature")
mfdobj_x <- get_mfd_list(air[fun_covariates], lambda = 1e-2)
get_outliers_mfd(mfdobj_x)
```

| | |
|---------------------|---|
| get_sof_pc_outliers | <i>Get possible outliers of a training data set of a scalar-on-function regression model.</i> |
|---------------------|---|

Description

Get possible outliers of a training data set of a scalar-on-function regression model. It sets the training data set also as tuning data set for the calculation of control chart limits, and as phase II data set to compare monitoring statistics against the limits and identify possible outliers. This is only an empirical approach. It is advised to use methods appropriately designed for phase I monitoring to identify outliers.

Usage

```
get_sof_pc_outliers(y, mfdobj)
```

Arguments

`y` A numeric vector containing the observations of the scalar response variable.

`mfdobj` A multivariate functional data object of class `mfd` denoting the functional covariates.

Value

A character vector with the ids of functional observations signaled as possibly anomalous.

Examples

```
## Not run:
library(funcharts)
data("air")
air <- lapply(air, function(x) x[1:10, , drop = FALSE])
fun_covariates <- c("CO", "temperature")
mfdobj_x <- get_mfd_list(air[fun_covariates], lambda = 1e-2)
y <- rowMeans(air$NO2)
get_sof_pc_outliers(y, mfdobj_x)

## End(Not run)
```

inprod_mfd

Inner products of functional data contained in mfd objects.

Description

Inner products of functional data contained in `mfd` objects.

Usage

```
inprod_mfd(mfdobj1, mfdobj2 = NULL)
```

Arguments

`mfdobj1` A multivariate functional data object of class `mfd`.

`mfdobj2` A multivariate functional data object of class `mfd`. It must have the same functional variables as `mfdobj1`. If `NULL`, it is equal to `mfdobj1`.

Details

Note that L^2 inner products are not calculated for couples of functional data from different functional variables. This function is needed to calculate the inner product in the product Hilbert space in the case of multivariate functional data, which for each observation is the sum of the L^2 inner products obtained for each functional variable.

Value

a three-dimensional array of L^2 inner products. The first dimension is the number of functions in argument `mfdobj1`, the second dimension is the same thing for argument `mfdobj2`, the third dimension is the number of functional variables. If you sum values over the third dimension, you get a matrix of inner products in the product Hilbert space of multivariate functional data.

Examples

```
library(funcharts)
set.seed(123)
mfdobj1 <- data_sim_mfd()
mfdobj2 <- data_sim_mfd()
inprod_mfd(mfdobj1)
inprod_mfd(mfdobj1, mfdobj2)
```

| | |
|------------------------------|--|
| <code>inprod_mfd_diag</code> | <i>Inner product of two multivariate functional data objects, for each observation</i> |
|------------------------------|--|

Description

Inner product of two multivariate functional data objects, for each observation

Usage

```
inprod_mfd_diag(mfdobj1, mfdobj2 = NULL)
```

Arguments

| | |
|----------------------|---|
| <code>mfdobj1</code> | A multivariate functional data object of class <code>mfd</code> . |
| <code>mfdobj2</code> | A multivariate functional data object of class <code>mfd</code> , with the same number of functional variables and observations as <code>mfdobj1</code> . If <code>NULL</code> , then <code>mfdobj2=mfdobj1</code> . Default is <code>NULL</code> . |

Value

It calculates the inner product of two multivariate functional data objects. The main function `inprod` of the package `fda` calculates inner products among all possible couples of observations. This means that, if `mfdobj1` has n_1 observations and `mfdobj2` has n_2 observations, then for each variable $n_1 \times n_2$ inner products are calculated. However, often one is interested only in calculating the n inner products between the n observations of `mfdobj1` and the corresponding n observations of

mfdobj2. This function provides this "diagonal" inner products only, saving a lot of computation with respect to using `fda::inprod` and then extracting the diagonal elements. Note that the code of this function calls a modified version of `fda::inprod()`.

Examples

```
mfdobj <- data_sim_mfd()
inprod_mfd_diag(mfdobj)
```

| | |
|---------------------|-------------------------------------|
| <code>is.mfd</code> | <i>Confirm Object has Class mfd</i> |
|---------------------|-------------------------------------|

Description

Check that an argument is a multivariate functional data object of class `mfd`.

Usage

```
is.mfd(mfdobj)
```

Arguments

`mfdobj` An object to be checked.

Value

a logical value: TRUE if the class is correct, FALSE otherwise.

| | |
|------------------------|---|
| <code>lines_mfd</code> | <i>Add the plot of a new multivariate functional data object to an existing plot.</i> |
|------------------------|---|

Description

Add the plot of a new multivariate functional data object to an existing plot.

Usage

```
lines_mfd(  
  plot_mfd_obj,  
  mfdobj_new,  
  mapping = NULL,  
  data = NULL,  
  stat = "identity",  
  position = "identity",  
  na.rm = TRUE,  
  orientation = NA,  
  show.legend = NA,  
  inherit.aes = TRUE,  
  type_mfd = "mfd",  
  y_lim_equal = FALSE,  
  ...  
)
```

Arguments

| | |
|--------------|--|
| plot_mfd_obj | A plot produced by <code>link{plot_mfd}</code> |
| mfdobj_new | A new multivariate functional data object of class <code>mfd</code> to be plotted. |
| mapping | See plot_mfd . |
| data | See plot_mfd . |
| stat | See plot_mfd . |
| position | See plot_mfd . |
| na.rm | See plot_mfd . |
| orientation | See plot_mfd . |
| show.legend | See plot_mfd . |
| inherit.aes | See plot_mfd . |
| type_mfd | See plot_mfd . |
| y_lim_equal | See plot_mfd . |
| ... | See plot_mfd . |

Value

A plot of the multivariate functional data object added to the existing one.

Examples

```
library(funcharts)  
library(ggplot2)  
mfdobj1 <- data_sim_mfd()  
mfdobj2 <- data_sim_mfd()  
p <- plot_mfd(mfdobj1)  
lines_mfd(p, mfdobj_new = mfdobj2)
```

| | |
|----------|---|
| mean_mfd | <i>Mean Function for Multivariate Functional Data</i> |
|----------|---|

Description

Computes the mean function for a multivariate functional data object of class `mfd`.

Usage

```
mean_mfd(mfdobj)
```

Arguments

`mfdobj` An object of class `mfd` representing the multivariate functional data. It contains N observations of a p -dimensional multivariate functional variable.

Details

This function calculates the mean function for each dimension of the multivariate functional data by averaging the coefficients across all observations. The resulting object is a single observation containing the mean function for each dimension.

Value

An `mfd` object representing the mean function of the input data. The output contains one observation, representing the mean function for each dimension of the multivariate functional variable.

Examples

```
## Not run:  
library(funcharts)  
data(air)  
mfdobj <- get_mfd_list(air)  
mean_result <- mean_mfd(mfdobj)  
plot_mfd(mean_result)  
  
## End(Not run)
```

mfd

*Define a Multivariate Functional Data Object***Description**

This is the constructor function for objects of the mfd class. It is a wrapper to `fda::fd`, but it forces the `coef` argument to be a three-dimensional array of coefficients even if the functional data is univariate. Moreover, it allows to include the original raw data from which you get the smooth functional data. Finally, it also includes the matrix of precomputed inner products of the basis functions, which can be useful to speed up computations when calculating inner products between functional observations

Usage

```
mfd(coef, basisobj, fdnames = NULL, raw = NULL, id_var = NULL, B = NULL)
```

Arguments

| | |
|-----------------------|---|
| <code>coef</code> | <p>A three-dimensional array of coefficients:</p> <ul style="list-style-type: none"> • the first dimension corresponds to basis functions. • the second dimension corresponds to the number of multivariate functional observations. • the third dimension corresponds to variables. |
| <code>basisobj</code> | A functional basis object defining the basis, as provided to <code>fda::fd</code> , but there is no default. |
| <code>fdnames</code> | <p>A list of length 3, each member being a string vector containing labels for the levels of the corresponding dimension of the discrete data.</p> <p>The first dimension is for a single character indicating the argument values, i.e. the variable on the functional domain.</p> <p>The second is for replications, i.e. it denotes the functional observations.</p> <p>The third is for functional variables' names.</p> |
| <code>raw</code> | <p>A data frame containing the original discrete data. Default is NULL, however, if provided, it must contain:</p> <p>a column (indicated by the <code>id_var</code> argument) denoting the functional observations, which must correspond to values in <code>fdnames[[2]]</code>,</p> <p>a column named as <code>fdnames[[1]]</code>, returning the argument values of each function</p> <p>as many columns as the functional variables, named as in <code>fdnames[[3]]</code>, containing the discrete functional values for each variable.</p> |
| <code>id_var</code> | A single character value indicating the column in the <code>raw</code> argument containing the functional observations (as in <code>fdnames[[2]]</code>), default is NULL. |
| <code>B</code> | A matrix with the inner products of the basis functions. If NULL, it is calculated from the basis object provided. Default is NULL. |

Details

To check that an object is of this class, use function `is.mfd`.

Value

A multivariate functional data object (i.e., having class `mfd`), which is a list with components named `coefs`, `basis`, and `fdnames`, as for class `fd`, with possibly in addition the components `raw` and `id_var`.

References

Ramsay, James O., and Silverman, Bernard W. (2006), *Functional Data Analysis*, 2nd ed., Springer, New York.

Ramsay, James O., and Silverman, Bernard W. (2002), *Applied Functional Data Analysis*, Springer, New York.

Examples

```
library(funcharts)
library(fda)
set.seed(0)
nobs <- 5
nbasis <- 10
nvar <- 2
coef <- array(rnorm(nobs * nbasis * nvar), dim = c(nbasis, nobs, nvar))
bs <- create.bspline.basis(rangeval = c(0, 1), nbasis = nbasis)
mfdobj <- mfd(coef = coef, basisobj = bs)
plot_mfd(mfdobj)
```

mFPCA

Mixed Functional Principal Component Analysis (mFPCA)

Description

This function implements the mFPCA.

Usage

```
mFPCA(x_fd, h_fd = NULL, k_weights = "equal", ncom = "ptv", par_ncom = 0.9)
```

Arguments

| | |
|------------------------|--|
| <code>x_fd</code> | An object of class <code>fd</code> corresponding to the registered functions. |
| <code>h_fd</code> | An object of class <code>fd</code> corresponding to the warping functions. |
| <code>k_weights</code> | The vector of the four constants in the inner product computation. If "equal", the choice of Centofanti et al. (2024) is used. |

| | |
|----------|--|
| ncom | It is the way to select the number of principal components. If "ptv", it is selected considering the percentage of the total variability explained. If "kaiserrule", it is selected considering the Kaiser rule. The number of principal components may be indicated directly as an integer as well. |
| par_ncom | If ncom="ptv", the threshold for the percentage of the total variability explained. If ncom="kaiserrule", the threshold for the Kaiser rule. Otherwise, this parameter is not considered. |

Value

A list containing the following arguments:

eigfun_fd A List of functions corresponding to the functional part of the principal components.

eigvect_sc A matrix corresponding to the scalar part of the principal components.

scores Scores corresponding to x_fd and h_fd.

values Eigenvalues corresponding to the selected principal components.

varprop Variance proportion explained by each principal component.

k_weights The vector of the four constants in the inner product computation.

x_fd_list A List of two elements: the list of the registered functions and the list of the centred log-ratio transformation of the first derivatives of the normalized warping functions.

sc_mat Two column matrix corresponding to the scalar part of the observations used.

mean_fd_list Mean functions of the functional part.

mean_sc_mat Means of the scalar part.

sd_fd_list The standard deviation of the functional part.

sd_sc_mat Standard deviations of the scalar part.

h_fd An object of class fd corresponding to the warping functions.

x_fd An object of class fd corresponding to the registered functions. ind_var Additional parameter used in FRTM_PhaseI.

Author(s)

F. Centofanti

References

Centofanti, F., A. Lepore, M. Kulahci, and M. P. Spooner (2024). Real-time monitoring of functional data. Accepted for publication in *Journal of Quality Technology*.

Examples

```
library(funcharts)

data <- simulate_data_FRTM(n_obs = 100)
X <- sapply(1:100, function(ii)
  data$x_true[[ii]])
x_fd <-
```

```

fda::smooth.basis(y = X,
                  argvals = data$grid,
                  fda::create.bspline.basis(c(0, 1), 30))$fd
H <- sapply(1:100, function(ii)
  data$h[[ii]])
h_fd <-
  fda::smooth.basis(y = H,
                    argvals = data$grid,
                    fda::create.bspline.basis(c(0, 1), 30))$fd
mod_mFPCA <- mFPCA(x_fd, h_fd, ncom = "ptv", par_ncom = 0.95)
plot(mod_mFPCA)

```

norm.mfd

Norm of Multivariate Functional Data

Description

Norm of multivariate functional data contained in a mfd object.

Usage

```
norm.mfd(mfdobj)
```

Arguments

mfdobj A multivariate functional data object of class mfd.

Value

A vector of length equal to the number of replications in mfdobj, containing the norm of each multivariate functional observation in the product Hilbert space, i.e. the sum of L^2 norms for each functional variable.

Examples

```

library(funcharts)
mfdobj <- data_sim_mfd()
norm.mfd(mfdobj)

```

| | |
|---------|---|
| OEBFDTW | <i>Open-end/open-begin Functional Dynamic Time Warping (OEB-FDTW)</i> |
|---------|---|

Description

This function implements the OEB-FDTW.

Usage

```
OEBFDTW(
  x_fd,
  template_fd,
  der_x_fd,
  der_template_fd,
  alpha_vec = c(0, 0.5, 1),
  fit_c = FALSE,
  N = 100,
  M = 50,
  smin = 0.01,
  smax = 1000,
  lambda = 10^-5,
  eta = 0.5,
  iter = 3,
  delta_xs = 0,
  delta_xe = 0,
  delta_ys = 0,
  delta_ye = 0,
  der_0 = NULL,
  seq_t = NULL,
  get_fd = "no",
  n_basis_x = NULL
)
```

Arguments

| | |
|------------------------------|--|
| <code>x_fd</code> | An object of class <code>fd</code> corresponding to the misaligned function. |
| <code>template_fd</code> | An object of class <code>fd</code> corresponding to the template function. |
| <code>der_x_fd</code> | An object of class <code>fd</code> corresponding to the first derivative of <code>x_fd</code> . |
| <code>der_template_fd</code> | An object of class <code>fd</code> corresponding to the first derivative of <code>template_fd</code> . |
| <code>alpha_vec</code> | Grid of values to find the optimal value of α_i . |
| <code>fit_c</code> | If TRUE, the value of the objective function without the penalization evaluated at the solution is returned. |
| <code>N</code> | The number N_t of evenly spaced values along the template domain \mathcal{D}_Y . |

| | |
|-----------|--|
| M | The number M_x of evenly spaced values along the functional observation domain \mathcal{D}_{X_i} . |
| smin | The minimum values allowed for the first derivative of the warping function h_i . If NULL, in FRTM_PhaseI, it is set as 0.001 multiplied by the ratio between the size of the monitoring and template domains. |
| smax | The maximum values allowed for the first derivative of the warping function h_i . If NULL, in FRTM_PhaseI, it is set as 100 multiplied by the ratio between the size of the monitoring and template domains. |
| lambda | The smoothing parameter λ_i . |
| eta | Fraction η for updating the constraint bounds to reduce the error associated to the discretization (Deriso and Boyd, 2022). |
| iter | Number of iteration in the iterative refinement to reduce the error associated to the discretization (Deriso and Boyd, 2022). |
| delta_xs | Maximum allowed misalignment at the beginning of the process along the misaligned function domain. |
| delta_xe | Maximum allowed misalignment at the end of the process along the misaligned function domain. |
| delta_ys | Maximum allowed misalignment at the beginning of the process along the template domain. |
| delta_ye | Maximum allowed misalignment at the end of the process along the template domain. |
| der_0 | The target values towards which shrinking the warping function slope. If NULL, it is equal to the ratio between the size of the domain of <code>x_fd</code> and the size of the domain of <code>template_fd</code> . |
| seq_t | Discretized sequence in the template domain \mathcal{D}_Y . If NULL, an equally spaced grid of length N in the template domain is used. |
| get_fd | If "x_reg", the registered function as a class fd object is returned. If "no", the registered function as a class fd object is not returned. |
| n_basis_x | Number of basis to obtain the registered function. If NULL, it is set as 0.5 the length of the optimal path. |

Value

A list containing the following arguments:

mod that is a list composed by

- `h_fd`: The estimated warping function.
- `x_reg`: The registered function.
- `h_list`: A list containing the discretized warping function for each iteration of the iterative refinement.
- `min_cost`: Optimal value of the objective function.
- `lambda`: The smoothing parameter λ .
- `alpha`: Optimal value of the parameter α_i .

obj Values of the objective function for each value in alpha_vec.
 fit Values of the objective function without the penalization for each value in alpha_vec.
 obj_opt Optimal value of the objective function.
 fit_opt Optimal value of the objective function without the penalization.

Author(s)

F. Centofanti

References

Centofanti, F., A. Lepore, M. Kulahci, and M. P. Spooner (2024). Real-time monitoring of functional data. Accepted for publication in *Journal of Quality Technology*.
 Deriso, D. and S. Boyd (2022). A general optimization framework for dynamic time warping. *Optimization and Engineering*, 1-22.

Examples

```
set.seed(1)
data <- simulate_data_FRTM(n_obs = 100)

dom <- c(0, 1)
basis_x <- fda::create.bspline.basis(c(0, 1), nbasis = 30)
x_fd <-
  fda::smooth.basis(data$grid_i[[1]] / max(data$grid_i[[1]]), data$x_err[[1]], basis_x)$fd
template_fd <-
  fda::smooth.basis(data$grid_template, data$template, basis_x)$fd
der_x_fd <- fda::deriv.fd(x_fd, 1)
der_template_fd <- fda::deriv.fd(template_fd, 1)

mod <-
  OEBFDTW(x_fd, template_fd, der_x_fd, der_template_fd, get_fd = "x_reg")
```

| | |
|----------|--|
| par.FDTW | <i>Setting open-end/open-begin functional dynamic time warping (OEB-FDTW) defaults</i> |
|----------|--|

Description

This is an internal function of package FRTM which allows controlling the parameters to implement the OEB-FDTW in the FRTM method.

Usage

```

par.FDTW(
  N = 100,
  M = 50,
  smin = NULL,
  smax = NULL,
  alpha_vec = c(0, 0.5, 1),
  frac_oeob = 0.1,
  eta = 0.5,
  iter = 3,
  template = "Procrustes",
  grid_tem = NULL,
  index_tem = NULL,
  iter_tem = 2,
  lambda = c(0, 10^seq(-8, -2, by = 0.25), 10^5),
  threshold = 0.01,
  seq_t = seq(0.01, 1, length.out = 100)
)

```

Arguments

| | |
|-----------|---|
| N | The number N_t of evenly spaced values along the template domain \mathcal{D}_Y . |
| M | The number M_x of evenly spaced values along the functional observation domain \mathcal{D}_{X_i} . |
| smin | The minimum values allowed for the first derivative of the warping function h_i . If NULL, in FRTM_PhaseI, it is set as 0.001 multiplied by the ratio between the size of the monitoring and template domains. |
| smax | The maximum values allowed for the first derivative of the warping function h_i . If NULL, in FRTM_PhaseI, it is set as 100 multiplied by the ratio between the size of the monitoring and template domains. |
| alpha_vec | Grid of values to find the optimal value of α_i . |
| frac_oeob | Fraction of \mathcal{D}_Y and \mathcal{D}_{X_i} to obtain $\delta_{t,s}$, $\delta_{t,e}$, $\delta_{x,s}$ and $\delta_{x,e}$. |
| eta | Fraction η for updating the constraint bounds to reduce the error associated to the discretization (Deriso and Boyd, 2022). |
| iter | Number of iteration in the iterative refinement to reduce the error associated to the discretization (Deriso and Boyd, 2022). |
| template | If "Procrustes", the Procrustes fitting process is used to select the template function. If numeric, the discrete observations of the template function. |
| grid_tem | If template is numeric, a vector of time points where the discrete observations of the template function are sampled. |
| index_tem | If NULL and template="Procrustes", the function in the training set, whose domain length is nearest the median domain length, is chosen as initial estimate of the template function. If an integer and template="Procrustes", the index_tem function in the training set is chosen as initial estimate of the template function. If template is numeric, this parameter is not used. |

| | |
|-----------|---|
| iter_tem | Number of iterations in the Procrustes fitting process. |
| lambda | Grid of smoothing parameters to evaluate the average curve distance (ACD). |
| threshold | The fraction δ of the difference between the maximum and the minimum distance in the selection of the smoothing parameter via the ACD. |
| seq_t | Discretized sequence in the template domain \mathcal{D}_Y . |

Author(s)

F. Centofanti

References

Deriso, D. and S. Boyd (2022). A general optimization framework for dynamic time warping. *Optimization and Engineering*, 1-22.

See Also[FRTM_PhaseI](#)**Examples**

```
library(funcharts)
par.FDTW()
```

| | |
|-----------|---|
| par.mFPCA | <i>Setting mixed functional principal component analysis (mFPCA) defaults</i> |
|-----------|---|

Description

This is an internal function of package FRTM which allows controlling the parameters used in the mFPCA in the FRTM method.

Usage

```
par.mFPCA(perc_pca = 0.9, perc_basis_x_pca = 1, perc_basis_h = 0.2)
```

Arguments

| | |
|------------------|--|
| perc_pca | Percentage of the total variability used to select the number L of principal components. |
| perc_basis_x_pca | Multiplied by the maximum number of basis of the registered functions for each time point in \mathcal{D}_Y , it is the number of basis functions of the registered functions in the mFPCA. |
| perc_basis_h | Multiplied by the mean number of basis of the warping functions for each time point in \mathcal{D}_Y , it is the number of basis functions of the warping functions in the mFPCA. |

See Also[FRTM_PhaseI](#)**Examples**

```
library(funcharts)
par.mFPCA()
```

par.rtr

Setting real-time registration step defaults

Description

This is an internal function of package FRTM which allows controlling the parameters to implement real-time registration step in the FRTM method.

Usage

```
par.rtr(
  seq_x = NULL,
  delta_d = 0.05,
  delta_v = 0.03,
  delta_c = 0.04,
  Delta = 0.1,
  length_grid_window = 10,
  length_grid_owindow = 20,
  eval_seq_der = seq(0.02, 0.1, length.out = 10),
  perc_basis_x_reg = 0.3
)
```

Arguments

| | |
|---------------------|--|
| seq_x | Discretized sequence in the monitoring domain \mathcal{D}_m . |
| delta_d | The parameter δ_d in the adaptive band constraint calculation. |
| delta_v | The parameter δ_v in the adaptive band constraint calculation. |
| delta_c | The parameter δ_c in the adaptive band constraint calculation. |
| Delta | The parameter Δ in the adaptive band constraint calculation. |
| length_grid_window | Number of points to be explored in the interval of the band constraint for each point in \mathcal{D}_m when the adaptive band constraint is considered. |
| length_grid_owindow | Number of points to be explored in the interval of the band constraint for each point in \mathcal{D}_m when the original band constraint is considered. |
| eval_seq_der | If multiplied by the template domain range, the distances from the domain right boundaries over which are calculated the first derivative to mitigate the effects of possible estimation errors in the adaptive band constraint calculation. |

perc_basis_x_reg

Multiplied by the number of observed discrete points, it is the number of basis functions used in the real-time registration step for each time point. This latter number cannot be greater than `n_basis_xall`.

Author(s)

F. Centofanti

See Also

[FRTM_PhaseI](#)

Examples

```
library(funcharts)
par.rtr()
```

pca_mfd

Multivariate functional principal components analysis

Description

Multivariate functional principal components analysis (MFPCA) performed on an object of class `mfd`. It is a wrapper to `fda::pca.fd`, providing some additional arguments.

Usage

```
pca_mfd(mfdobj, scale = TRUE, nharm = 20)
```

Arguments

| | |
|---------------------|--|
| <code>mfdobj</code> | A multivariate functional data object of class <code>mfd</code> . |
| <code>scale</code> | If <code>TRUE</code> , it scales data before doing MFPCA using <code>scale_mfd</code> . Default is <code>TRUE</code> . |
| <code>nharm</code> | Number of multivariate functional principal components to be calculated. Default is 20. |

Value

Modified `pca.fd` object, with multivariate functional principal component scores summed over variables (`fda::pca.fd` returns an array of scores when providing a multivariate functional data object). Moreover, the multivariate functional principal components given in `harmonics` are converted to the `mfd` class.

See Also

[scale_mfd](#)

Examples

```
library(funcharts)
mfdoobj <- data_sim_mfd()
pca_obj <- pca_mfd(mfdoobj)
plot_pca_mfd(pca_obj)
```

| | |
|-------------------|---|
| pca_mfd_real_time | <i>Get a list of multivariate functional principal component analysis models estimated on functional data each evolving up to an intermediate domain point.</i> |
|-------------------|---|

Description

This function produces a list of objects, each of them contains the result of applying [pca_mfd](#) to a multivariate functional data object evolved up to an intermediate domain point.

Usage

```
pca_mfd_real_time(mfdoobj_list, scale = TRUE, nharm = 20, ncores = 1)
```

Arguments

| | |
|--------------|--|
| mfdoobj_list | A list created using get_mfd_df_real_time or get_mfd_list_real_time , denoting a list of functional data objects, each evolving up to an intermediate domain point, with observations of the multivariate functional data. |
| scale | See pca_mfd . |
| nharm | See pca_mfd . |
| ncores | If you want parallelization, give the number of cores/threads to be used when creating objects separately for different instants. |

Value

A list of lists each produced by [pca_mfd](#), corresponding to a given instant.

Author(s)

C. Capezza

See Also

[pca_mfd](#)

Examples

```

library(funcharts)
data("air")
air <- lapply(air, function(x) x[1:10, , drop = FALSE])
mfdoobj_list <- get_mfd_list_real_time(air[c("CO", "temperature")],
                                     n_basis = 15,
                                     lambda = 1e-2,
                                     k_seq = seq(0.25, 1, length = 5))
mod_list <- pca_mfd_real_time(mfdoobj_list)

```

plot.FRTM_PhaseI *Plot the results of the Phase I and the Phase II of the FRTM*

Description

This function provides plots of the Hotelling's T^2 and SPE control charts.

Usage

```

## S3 method for class 'FRTM_PhaseI'
plot(x, ...)

## S3 method for class 'FRTM_PhaseII'
plot(x, ...)

```

Arguments

`x` The output of either FRTM_PhaseI or FRTM_PhaseII.

`...` A variable `ind_sel` could be provided to select some observations from either the tuning or monitoring set.

Value

No return value, called for side effects.

Examples

```

library(funcharts)
data <- simulate_data_FRTM(n_obs = 20)

data_oc <-
  simulate_data_FRTM(
    n_obs = 2,
    scenario = "1",
    shift = "OC_h",
    severity = 0.5
  )

```

```

lambda <- 10 ^ -5
max_x <- max(unlist(data$grid_i))
seq_t_tot <- seq(0, 1, length.out = 30)[-1]
seq_x <- seq(0.1, max_x, length.out = 10)

## Not run:
mod_phaseI_FRTM <- FRTM_PhaseI(
  data_tra = data,
  control.FDTW = list(
    M = 30,
    N = 30,
    lambda = lambda,
    seq_t = seq_t_tot,
    iter_tem = 1,
    iter = 1
  ),
  control.rtr = list(seq_x = seq_x)
)
mod_phaseII_FRTM <- FRTM_PhaseII(data_oc = data_oc , mod_phaseI = mod_phaseI_FRTM)

plot(mod_phaseI_FRTM)
plot(mod_phaseII_FRTM)

## End(Not run)

```

plot.mFPCA

Plot the results of the Mixed Functional Principal Component Analysis (mFPCA)

Description

This function provides plots of the principal components of the mFPCA.

Usage

```

## S3 method for class 'mFPCA'
plot(x, ...)

```

Arguments

| | |
|-----|--|
| x | The output of mFPCA. |
| ... | A variable type could be provided that can assume two values. If type="single", the principal components are plotted separately. If type="all", the principal components are plotted together. |

Value

No return value, called for side effects.

Examples

```
library(funcharts)

data <- simulate_data_FRTM(n_obs = 100)
X <- sapply(1:100, function(ii)
  data$x_true[[ii]])
x_fd <-
  fda::smooth.basis(y = X,
                    argvals = data$grid,
                    fda::create.bspline.basis(c(0, 1), 30))$fd
H <- sapply(1:100, function(ii)
  data$h[[ii]])
h_fd <-
  fda::smooth.basis(y = H,
                    argvals = data$grid,
                    fda::create.bspline.basis(c(0, 1), 30))$fd
mod_mFPCA <- mFPCA(x_fd, h_fd, ncom = "ptv", par_ncom = 0.95)
plot(mod_mFPCA)
```

plot_bifd

Plot a Bivariate Functional Data Object.

Description

Plot an object of class `bifd` using `ggplot2` and `geom_tile`. The object must contain only one single functional replication.

Usage

```
plot_bifd(bifd_obj, type_plot = "raster", phi = 40, theta = 40)
```

Arguments

| | |
|------------------------|---|
| <code>bifd_obj</code> | A bivariate functional data object of class <code>bifd</code> , containing one single replication. |
| <code>type_plot</code> | a character value. If "raster", it plots the bivariate functional data object as a raster image. If "contour", it produces a contour plot. If "perspective", it produces a perspective plot. Default value is "raster". |
| <code>phi</code> | If <code>type_plot=="perspective"</code> , it is the <code>phi</code> argument of the function <code>plot3D::persp3D</code> . |
| <code>theta</code> | If <code>type_plot=="perspective"</code> , it is the <code>theta</code> argument of the function <code>plot3D::persp3D</code> . |

Value

A `ggplot` with a `geom_tile` layer providing a plot of the bivariate functional data object as a heat map.

Examples

```
library(funcharts)
mfdoj <- data_sim_mfd(nobs = 1)
tp <- tensor_product_mfd(mfdoj)
plot_bifd(tp)
```

plot_bootstrap_sof_pc *Plot bootstrapped estimates of the scalar-on-function regression coefficient*

Description

Plot bootstrapped estimates of the scalar-on-function regression coefficient for empirical uncertainty quantification. For each iteration, a data set is sampled with replacement from the training data use to fit the model, and the regression coefficient is estimated.

Usage

```
plot_bootstrap_sof_pc(mod, nboot = 25, ncores = 1)
```

Arguments

| | |
|--------|--|
| mod | A list obtained as output from <code>sof_pc</code> , i.e. a fitted scalar-on-function linear regression model. |
| nboot | Number of bootstrap replicates |
| ncores | If you want estimate the bootstrap replicates in parallel, give the number of cores/threads. |

Value

A ggplot showing several bootstrap replicates of the multivariate functional coefficients estimated fitting the scalar-on-function linear model. Gray lines indicate the different bootstrap estimates, the black line indicate the estimate on the entire dataset.

Author(s)

C. Capezza

Examples

```
library(funcharts)
data("air")
air <- lapply(air, function(x) x[1:10, , drop = FALSE])
fun_covariates <- c("CO", "temperature")
mfdoj_x <- get_mfd_list(air[fun_covariates], lambda = 1e-2)
y <- rowMeans(air$NO2)
mod <- sof_pc(y, mfdoj_x)
```

```
plot_bootstrap_sof_pc(mod, nboot = 5)
```

plot_control_charts *Plot control charts*

Description

This function takes as input a data frame produced with functions such as [control_charts_pca](#) and [control_charts_sof_pc](#) and produces a ggplot with the desired control charts, i.e. it plots a point for each observation in the phase II data set against the corresponding control limits.

Usage

```
plot_control_charts(cclist, nobsI = 0)
```

Arguments

| | |
|--------|--|
| cclist | A data.frame produced by control_charts_pca , control_charts_sof_pc , regr_cc_fof , or regr_cc_sof . |
| nobsI | An integer indicating the first observations that are plotted in gray. It is useful when one wants to plot the phase I data set together with the phase II data. In that case, one needs to indicate the number of phase I observations included in cclist. Default is zero. |

Details

Out-of-control points are signaled by colouring them in red.

Value

A ggplot with the functional control charts.

Examples

```
library(funcharts)
data("air")
air <- lapply(air, function(x) x[1:100, , drop = FALSE])
fun_covariates <- c("CO", "temperature")
mfdobj_x <- get_mfd_list(air[fun_covariates],
                       n_basis = 15,
                       lambda = 1e-2)
mfdobj_y <- get_mfd_list(air["NO2"],
                       n_basis = 15,
                       lambda = 1e-2)
mfdobj_y1 <- mfdobj_y[1:60]
mfdobj_y_tuning <- mfdobj_y[61:90]
mfdobj_y2 <- mfdobj_y[91:100]
mfdobj_x1 <- mfdobj_x[1:60]
```

```

mfdoobj_x_tuning <- mfdoobj_x[61:90]
mfdoobj_x2 <- mfdoobj_x[91:100]
mod_fof <- fof_pc(mfdoobj_y1, mfdoobj_x1)
cclist <- regr_cc_fof(mod_fof,
                    mfdoobj_y_new = mfdoobj_y2,
                    mfdoobj_x_new = mfdoobj_x2,
                    mfdoobj_y_tuning = NULL,
                    mfdoobj_x_tuning = NULL)
plot_control_charts(cclist)

```

plot_control_charts_real_time

Plot real-time control charts

Description

This function produces a ggplot with the desired real-time control charts. It takes as input a list of data frames, produced with functions such as [regr_cc_fof_real_time](#) and [control_charts_sof_pc_real_time](#), and the id of the observations for which real-time control charts are desired to be plotted. For each control chart, the solid line corresponds to the profile of the monitoring statistic and it is compared against control limits plotted as dashed lines. If a line is outside its limits it is coloured in red.

Usage

```
plot_control_charts_real_time(cclist, id_num)
```

Arguments

| | |
|--------|--|
| cclist | A list of data frames, produced with functions such as regr_cc_fof_real_time and control_charts_sof_pc_real_time , |
| id_num | An index number giving the observation in the phase II data set to be plotted, i.e. 1 for the first observation, 2 for the second, and so on. |

Details

If the line, representing the profile of the monitoring statistic over the functional domain, is out-of-control, then it is coloured in red.

Value

A ggplot with the real-time functional control charts.

See Also

[regr_cc_fof_real_time](#), [control_charts_sof_pc_real_time](#)

Examples

```

library(funcharts)
data("air")
air1 <- lapply(air, function(x) x[1:8, , drop = FALSE])
air2 <- lapply(air, function(x) x[9:10, , drop = FALSE])
mfdobj_x1_list <- get_mfd_list_real_time(air1[c("CO", "temperature")],
                                       n_basis = 15,
                                       lambda = 1e-2,
                                       k_seq = c(0.5, 1))
mfdobj_x2_list <- get_mfd_list_real_time(air2[c("CO", "temperature")],
                                       n_basis = 15,
                                       lambda = 1e-2,
                                       k_seq = c(0.5, 1))

y1 <- rowMeans(air1$NO2)
y2 <- rowMeans(air2$NO2)
mod_list <- sof_pc_real_time(y1, mfdobj_x1_list)
cclist <- regr_cc_sof_real_time(
  mod_list = mod_list,
  y_new = y2,
  mfdobj_x_new = mfdobj_x2_list,
  include_covariates = TRUE)
plot_control_charts_real_time(cclist, 1)

```

plot_mfd

Plot a Multivariate Functional Data Object.

Description

Plot an object of class `mfd` using `ggplot2` and `patchwork`.

Usage

```

plot_mfd(
  mfdobj,
  mapping = NULL,
  data = NULL,
  stat = "identity",
  position = "identity",
  na.rm = TRUE,
  orientation = NA,
  show.legend = NA,
  inherit.aes = TRUE,
  type_mfd = "mfd",
  y_lim_equal = FALSE,
  ...
)

```

Arguments

| | |
|-------------|---|
| mfdobj | A multivariate functional data object of class mfd. |
| mapping | Set of aesthetic mappings additional to x and y as passed to the function <code>ggplot2::geom_line</code> . |
| data | A <code>data.frame</code> providing columns to create additional aesthetic mappings. It must contain a factor column "id" with the replication values as in <code>mfdobj\$fdnames[[2]]</code> . If it contains a column "var", this must contain the functional variables as in <code>mfdobj\$fdnames[[3]]</code> . |
| stat | See <code>ggplot2::geom_line</code> . |
| position | See <code>ggplot2::geom_line</code> . |
| na.rm | See <code>ggplot2::geom_line</code> . |
| orientation | See <code>ggplot2::geom_line</code> . |
| show.legend | See <code>ggplot2::geom_line</code> . |
| inherit.aes | See <code>ggplot2::geom_line</code> . |
| type_mfd | A character value equal to "mfd" or "raw". If "mfd", the smoothed functional data are plotted, if "raw", the original discrete data are plotted. |
| y_lim_equal | A logical value. If TRUE, the limits of the y-axis are the same for all functional variables. If FALSE, limits are different for each variable. Default value is FALSE. |
| ... | See <code>ggplot2::geom_line</code> . |

Value

A plot of the multivariate functional data object.

Examples

```
library(funcharts)
library(ggplot2)
mfdobj <- data_sim_mfd()
ids <- mfdobj$fdnames[[2]]
df <- data.frame(id = ids, first_two_obs = ids %in% c("rep1", "rep2"))
plot_mfd(mapping = aes(colour = first_two_obs),
          data = df,
          mfdobj = mfdobj)
```

plot_mon

Plot multivariate functional object over the training data set

Description

This function plots selected functions in a phase_II monitoring data set against the corresponding training data set to be compared.

Usage

```
plot_mon(cclist, fd_train, fd_test, plot_title = FALSE, print_id = FALSE)
```

Arguments

| | |
|------------|--|
| cclist | A data.frame produced by control_charts_pca , control_charts_sof_pc , regr_cc_fof , or regr_cc_sof . |
| fd_train | An object of class mfd containing the training data set of the functional variables. They are plotted in gray in the background. |
| fd_test | An object of class mfd containing the phase II data set of the functional variables to be monitored. They are coloured in black or red on the foreground. |
| plot_title | A logical value. If TRUE, it prints the title with the observation name. Default is FALSE. |
| print_id | A logical value. If TRUE, and also plot_title is TRUE, it prints also the id of the observation in the title of the ggplot. Default is FALSE |

Value

A ggplot of the multivariate functional data. In particular, the multivariate functional data given in `fd_train` are plotted on the background in gray, while the multivariate functional data given in `fd_test` are plotted on the foreground, the colour of each curve is black or red depending on if that curve was signal as anomalous by at least a contribution plot.

Examples

```
library(funcharts)
data("air")
air <- lapply(air, function(x) x[201:300, , drop = FALSE])
fun_covariates <- c("CO", "temperature")
mfdobj_x <- get_mfd_list(air[fun_covariates],
                       n_basis = 15,
                       lambda = 1e-2)

y <- rowMeans(air$NO2)
y1 <- y[1:60]
y_tuning <- y[61:90]
y2 <- y[91:100]
mfdobj_x1 <- mfdobj_x[1:60]
mfdobj_x_tuning <- mfdobj_x[61:90]
mfdobj_x2 <- mfdobj_x[91:100]
mod <- sof_pc(y1, mfdobj_x1)
cclist <- regr_cc_sof(object = mod,
                    y_new = y2,
                    mfdobj_x_new = mfdobj_x2,
                    y_tuning = y_tuning,
                    mfdobj_x_tuning = mfdobj_x_tuning,
                    include_covariates = TRUE)

get_ooc(cclist)
cont_plot(cclist, 3)
plot_mon(cclist, fd_train = mfdobj_x1, fd_test = mfdobj_x2[3])
```

plot_pca_mfd *Plot the harmonics of a pca_mfd object*

Description

Plot the harmonics of a `pca_mfd` object

Usage

```
plot_pca_mfd(pca, harm = 0, scaled = FALSE)
```

Arguments

| | |
|---------------------|---|
| <code>pca</code> | A fitted multivariate functional principal component analysis (MFPCA) object of class <code>pca_mfd</code> . |
| <code>harm</code> | A vector of integers with the harmonics to plot. If 0, all harmonics are plotted. Default is 0. |
| <code>scaled</code> | If TRUE, eigenfunctions are multiplied by the square root of the corresponding eigenvalues, if FALSE they are not scaled and all have unit norm. Default is FALSE |

Value

A ggplot of the harmonics/multivariate functional principal components contained in the object `pca`.

Examples

```
library(funcharts)
mfdoobj <- data_sim_mfd()
pca_obj <- pca_mfd(mfdoobj)
plot_pca_mfd(pca_obj)
```

predict_fof_pc *Use a function-on-function linear regression model for prediction*

Description

Predict new observations of the functional response variable and calculate the corresponding prediction error (and their standardized or studentized version) given new observations of functional covariates and a fitted function-on-function linear regression model.

Usage

```
predict_fof_pc(object, mfdoobj_y_new, mfdoobj_x_new)
```


Arguments

| | |
|--------------|--|
| object | A list obtained as output from fof_pc, i.e. a fitted function-on-function linear regression model. |
| mfdobj_y_new | An object of class mfd containing new observations of the functional response. |
| mfdobj_x_new | An object of class mfd containing new observations of the functional covariates. |

Value

A list of mfd objects. It contains:

- pred_error: the prediction error of the standardized functional response variable,
- pred_error_original_scale: the prediction error of the functional response variable on the original scale,
- y_hat_new: the prediction of the functional response observations on the original scale,
- y_z_new: the standardized version of the functional response observations provided in mfdobj_y_new,
- y_hat_z_new: the prediction of the functional response observations on the standardized/studentized scale.

Author(s)

C. Capezza, F. Centofanti

References

Centofanti F, Lepore A, Menafoglio A, Palumbo B, Vantini S. (2021) Functional Regression Control Chart. *Technometrics*, 63(3), 281–294. doi:[10.1080/00401706.2020.1753581](https://doi.org/10.1080/00401706.2020.1753581)

Examples

```
library(funcharts)
data("air")
air <- lapply(air, function(x) x[1:10, , drop = FALSE])
fun_covariates <- c("CO", "temperature")
mfdobj_x <- get_mfd_list(air[fun_covariates], lambda = 1e-2)
mfdobj_y <- get_mfd_list(air["NO2"], lambda = 1e-2)
mod <- fof_pc(mfdobj_y, mfdobj_x)
predict_fof_pc(mod,
               mfdobj_y_new = mfdobj_y,
               mfdobj_x_new = mfdobj_x)
```

predict_sof_pc *Use a scalar-on-function linear regression model for prediction*

Description

Predict new observations of the scalar response variable and calculate the corresponding prediction error, with prediction interval limits, given new observations of functional covariates and a fitted scalar-on-function linear regression model

Usage

```
predict_sof_pc(
  object,
  y_new = NULL,
  mfdobj_x_new = NULL,
  alpha = 0.05,
  newdata
)
```

Arguments

| | |
|--------------|--|
| object | A list obtained as output from sof_pc, i.e. a fitted scalar-on-function linear regression model. |
| y_new | A numeric vector containing the new observations of the scalar response variable to be predicted. |
| mfdobj_x_new | An object of class mfd containing new observations of the functional covariates. If NULL, it is set as the functional covariates data used for model fitting. |
| alpha | A numeric value indicating the Type I error for the regression control chart and such that this function returns the 1-alpha prediction interval on the response. Default is 0.05. |
| newdata | Deprecated, use mfdobj_x_new argument. |

Value

A data.frame with as many rows as the number of functional replications in newdata, with the following columns:

- fit: the predictions of the response variable corresponding to new_data,
- lwr: lower limit of the 1-alpha prediction interval on the response, based on the assumption that it is normally distributed.
- upr: upper limit of the 1-alpha prediction interval on the response, based on the assumption that it is normally distributed.
- res: the residuals obtained as the values of y_new minus their fitted values. If the scalar-on-function model has been fitted with type_residual == "studentized", then the studentized residuals are calculated.

Author(s)

C. Capezza

Examples

```
library(funcharts)
data("air")
air <- lapply(air, function(x) x[1:10, , drop = FALSE])
fun_covariates <- c("CO", "temperature")
mfdoobj_x <- get_mfd_list(air[fun_covariates], lambda = 1e-2)
y <- rowMeans(air$NO2)
mod <- sof_pc(y, mfdoobj_x)
predict_sof_pc(mod)
```

rbind_mfd

*Bind replications of two Multivariate Functional Data Objects***Description**

Bind replications of two Multivariate Functional Data Objects

Usage

```
rbind_mfd(mfdoobj1, mfdoobj2)
```

Arguments

| | |
|----------|--|
| mfdoobj1 | An object of class mfd, with the same variables of mfdoobj2 and different replication names with respect to mfdoobj2. |
| mfdoobj2 | An object of class mfd, with the same variables of mfdoobj1, and different replication names with respect to mfdoobj1. |

Value

An object of class mfd, whose variables are the same of mfdoobj1 and mfdoobj2 and whose replications are the union of the replications in mfdoobj1 and mfdoobj2.

Examples

```
library(funcharts)
mfdoobj1 <- data_sim_mfd(nvar = 3, nobs = 4)
mfdoobj2 <- data_sim_mfd(nvar = 3, nobs = 5)
dimnames(mfdoobj2$coefs)[[2]] <-
  mfdoobj2$fdnames[[2]] <-
  c("rep11", "rep12", "rep13", "rep14", "rep15")
mfdoobj_rbind <- rbind_mfd(mfdoobj1, mfdoobj2)
plot_mfd(mfdoobj_rbind)
```

regr_cc_fof

*Functional Regression Control Chart***Description**

It builds a data frame needed to plot the Functional Regression Control Chart introduced in Centofanti et al. (2021), for monitoring a functional quality characteristic adjusted for by the effect of multivariate functional covariates, based on a fitted function-on-function linear regression model. The training data have already been used to fit the model. An optional tuning data set can be provided that is used to estimate the control chart limits. A phase II data set contains the observations to be monitored with the control charts. It also allows to jointly monitor the multivariate functional covariates.

Usage

```
regr_cc_fof(
  object,
  mfdobj_y_new,
  mfdobj_x_new,
  mfdobj_y_tuning = NULL,
  mfdobj_x_tuning = NULL,
  alpha = 0.05,
  include_covariates = FALSE,
  absolute_error = FALSE
)
```

Arguments

| | |
|------------------------------|---|
| <code>object</code> | A list obtained as output from <code>fof_pc</code> , i.e. a fitted function-on-function linear regression model. |
| <code>mfdobj_y_new</code> | An object of class <code>mfd</code> containing the phase II data set of the functional response observations to be monitored. |
| <code>mfdobj_x_new</code> | An object of class <code>mfd</code> containing the phase II data set of the functional covariates observations to be monitored. |
| <code>mfdobj_y_tuning</code> | An object of class <code>mfd</code> containing the tuning data set of the functional response observations, used to estimate the control chart limits. If <code>NULL</code> , the training data, i.e. the data used to fit the function-on-function linear regression model, are also used as the tuning data set, i.e. <code>mfdobj_y_tuning=object\$pca_y\$data</code> . Default is <code>NULL</code> . |
| <code>mfdobj_x_tuning</code> | An object of class <code>mfd</code> containing the tuning data set of the functional covariates observations, used to estimate the control chart limits. If <code>NULL</code> , the training data, i.e. the data used to fit the function-on-function linear regression model, are also used as the tuning data set, i.e. <code>mfdobj_x_tuning=object\$pca_x\$data</code> . Default is <code>NULL</code> . |

- alpha** If it is a number between 0 and 1, it defines the overall type-I error probability. By default, it is equal to 0.05 and the Bonferroni correction is applied by setting the type-I error probabilities equal to $\alpha/2$ in the Hotelling's T2 and SPE control charts. If `include_covariates` is TRUE, i.e., the Hotelling's T2 and SPE control charts are built also on the multivariate functional covariates, then the Bonferroni correction is applied by setting the type-I error probability in the four control charts equal to $\alpha/4$. If you want to set manually the Type-I error probabilities, then the argument `alpha` must be a named list with elements named as `T2`, `spe`, `T2_x` and `spe_x`, respectively, containing the desired Type I error probability of the T2 and SPE control charts for the functional response and the multivariate functional covariates, respectively.
- include_covariates** If TRUE, also functional covariates are monitored through `control_charts_pca`. If FALSE, only the functional response, conditionally on the covariates, is monitored.
- absolute_error** A logical value that, if `include_covariates` is TRUE, is passed to `control_charts_pca`.

Value

A data.frame containing the output of the function `control_charts_pca` applied to the prediction errors.

Author(s)

F. Centofanti

References

Centofanti F, Lepore A, Menafoglio A, Palumbo B, Vantini S. (2021) Functional Regression Control Chart. *Technometrics*, 63(3), 281–294. doi:10.1080/00401706.2020.1753581

See Also

[control_charts_pca](#)

Examples

```
library(funcharts)
data("air")
air <- lapply(air, function(x) x[1:100, , drop = FALSE])
fun_covariates <- c("CO", "temperature")
mfdobj_x <- get_mfd_list(air[fun_covariates],
                       n_basis = 15,
                       lambda = 1e-2)
mfdobj_y <- get_mfd_list(air["NO2"],
                       n_basis = 15,
                       lambda = 1e-2)
mfdobj_y1 <- mfdobj_y[1:60]
mfdobj_y_tuning <- mfdobj_y[61:90]
mfdobj_y2 <- mfdobj_y[91:100]
```

```

mfdobj_x1 <- mfdobj_x[1:60]
mfdobj_x_tuning <- mfdobj_x[61:90]
mfdobj_x2 <- mfdobj_x[91:100]
mod_fof <- fof_pc(mfdobj_y1, mfdobj_x1)
cclist <- regr_cc_fof(mod_fof,
                    mfdobj_y_new = mfdobj_y2,
                    mfdobj_x_new = mfdobj_x2,
                    mfdobj_y_tuning = NULL,
                    mfdobj_x_tuning = NULL)
plot_control_charts(cclist)

```

regr_cc_fof_real_time *Real-time functional regression control chart*

Description

This function produces a list of data frames, each of them is produced by `regr_cc_fof` and is needed to plot control charts for monitoring in real time a functional quality characteristic adjusted for the effect of multivariate functional covariates.

Usage

```

regr_cc_fof_real_time(
  mod_list,
  mfdobj_y_new_list,
  mfdobj_x_new_list,
  mfdobj_y_tuning_list = NULL,
  mfdobj_x_tuning_list = NULL,
  alpha = 0.05,
  include_covariates = FALSE,
  absolute_error = FALSE,
  ncores = 1
)

```

Arguments

- `mod_list` A list of lists produced by `fof_pc_real_time`, containing a list of function-on-function linear regression models estimated on functional data each evolving up to an intermediate domain point.
- `mfdobj_y_new_list` A list created using `get_mfd_df_real_time` or `get_mfd_list_real_time`, denoting a list of functional data objects in the phase II monitoring data set, each evolving up to an intermediate domain point, with observations of the functional response variable. The length of this list and `mod_list` must be equal, and their elements in the same position in the list must correspond to the same intermediate domain point.

`mfdobj_x_new_list`

A list created using `get_mfd_df_real_time` or `get_mfd_list_real_time`, denoting a list of functional data objects in the phase II monitoring data set, each evolving up to an intermediate domain point, with observations of the multivariate functional covariates. The length of this list and `mod_list` must be equal, and their elements in the same position in the list must correspond to the same intermediate domain point.

`mfdobj_y_tuning_list`

A list created using `get_mfd_df_real_time` or `get_mfd_list_real_time`, denoting a list of functional data objects in the tuning data set (used to estimate control chart limits), each evolving up to an intermediate domain point, with observations of the functional response variable. The length of this list and `mod_list` must be equal, and their elements in the same position in the list must correspond to the same intermediate domain point. If NULL, the training data, i.e. the functional response in `mod_list`, is also used as the tuning data set. Default is NULL.

`mfdobj_x_tuning_list`

A list created using `get_mfd_df_real_time` or `get_mfd_list_real_time`, denoting a list of functional data objects in the tuning data set (used to estimate control chart limits), each evolving up to an intermediate domain point, with observations of the multivariate functional covariates. The length of this list and `mod_list` must be equal, and their elements in the same position in the list must correspond to the same intermediate domain point. If NULL, the training data, i.e. the functional covariates in `mod_list`, are also used as the tuning data set. Default is NULL.

`alpha` See `regr_cc_fof`.

`include_covariates`
See `regr_cc_fof`.

`absolute_error` See `regr_cc_fof`.

`ncores` If you want parallelization, give the number of cores/threads to be used when creating objects separately for different instants.

Value

A list of data.frames each produced by `regr_cc_fof`, corresponding to a given instant.

See Also

`fof_pc_real_time`, `regr_cc_fof`

Examples

```
library(funcharts)
data("air")
air1 <- lapply(air, function(x) x[1:8, , drop = FALSE])
air2 <- lapply(air, function(x) x[9:10, , drop = FALSE])
mfdobj_x1_list <- get_mfd_list_real_time(air1[c("CO", "temperature")],
                                       n_basis = 15,
                                       lambda = 1e-2,
```

```

                                k_seq = c(0.5, 1))
mfdobj_x2_list <- get_mfd_list_real_time(air2[c("CO", "temperature")],
                                n_basis = 15,
                                lambda = 1e-2,
                                k_seq = c(0.5, 1))
mfdobj_y1_list <- get_mfd_list_real_time(air1["NO2"],
                                n_basis = 15,
                                lambda = 1e-2,
                                k_seq = c(0.5, 1))
mfdobj_y2_list <- get_mfd_list_real_time(air2["NO2"],
                                n_basis = 15,
                                lambda = 1e-2,
                                k_seq = c(0.5, 1))
mod_list <- fof_pc_real_time(mfdobj_y1_list, mfdobj_x1_list)
cclist <- regr_cc_fof_real_time(
  mod_list = mod_list,
  mfdobj_y_new_list = mfdobj_y2_list,
  mfdobj_x_new_list = mfdobj_x2_list)
plot_control_charts_real_time(cclist, 1)

```

regr_cc_sof

Scalar-on-Function Regression Control Chart

Description

This function is deprecated. Use [regr_cc_sof](#). This function builds a data frame needed to plot the scalar-on-function regression control chart, based on a fitted function-on-function linear regression model and proposed in Capezza et al. (2020). If `include_covariates` is TRUE, it also plots the Hotelling's T2 and squared prediction error control charts built on the multivariate functional covariates.

Usage

```

regr_cc_sof(
  object,
  y_new,
  mfdobj_x_new,
  y_tuning = NULL,
  mfdobj_x_tuning = NULL,
  alpha = 0.05,
  parametric_limits = FALSE,
  include_covariates = FALSE,
  absolute_error = FALSE
)

```


Arguments

| | |
|---------------------------------|---|
| <code>object</code> | A list obtained as output from <code>sof_pc</code> , i.e. a fitted scalar-on-function linear regression model. |
| <code>y_new</code> | A numeric vector containing the observations of the scalar response variable in the phase II data set. |
| <code>mfdobj_x_new</code> | An object of class <code>mfd</code> containing the phase II data set of the functional covariates observations. |
| <code>y_tuning</code> | A numeric vector containing the observations of the scalar response variable in the tuning data set. If <code>NULL</code> , the training data, i.e. the data used to fit the scalar-on-function regression model, are also used as the tuning data set. Default is <code>NULL</code> . |
| <code>mfdobj_x_tuning</code> | An object of class <code>mfd</code> containing the tuning set of the multivariate functional data, used to estimate the control chart limits. If <code>NULL</code> , the training data, i.e. the data used to fit the scalar-on-function regression model, are also used as the tuning data set. Default is <code>NULL</code> . |
| <code>alpha</code> | If it is a number between 0 and 1, it defines the overall type-I error probability. If <code>include_covariates</code> is <code>TRUE</code> , i.e., also the Hotelling's T2 and SPE control charts are built on the functional covariates, then the Bonferroni correction is applied by setting the type-I error probability in the three control charts equal to $\alpha/3$. In this last case, if you want to set manually the Type-I error probabilities, then the argument <code>alpha</code> must be a named list with three elements, named <code>T2</code> , <code>spe</code> and <code>y</code> , respectively, each containing the desired Type I error probability of the corresponding control chart, where <code>y</code> refers to the regression control chart. Default value is 0.05. |
| <code>parametric_limits</code> | If <code>TRUE</code> , the limits are calculated based on the normal distribution assumption on the response variable, as in Capezza et al. (2020). If <code>FALSE</code> , the limits are calculated nonparametrically as empirical quantiles of the distribution of the residuals calculated on the tuning data set. The default value is <code>FALSE</code> . |
| <code>include_covariates</code> | If <code>TRUE</code> , also functional covariates are monitored through <code>control_charts_pca</code> . If <code>FALSE</code> , only the scalar response, conditionally on the covariates, is monitored. |
| <code>absolute_error</code> | A logical value that, if <code>include_covariates</code> is <code>TRUE</code> , is passed to <code>control_charts_pca</code> . |

Details

The training data have already been used to fit the model. An additional tuning data set can be provided that is used to estimate the control chart limits. A phase II data set contains the observations to be monitored with the built control charts.

Value

A data.frame with as many rows as the number of functional replications in `mfdobj_x_new`, with the following columns:

- `y_hat`: the predictions of the response variable corresponding to `mfdobj_x_new`,
- `y`: the same as the argument `y_new` given as input to this function,
- `lwr`: lower limit of the $1-\alpha$ prediction interval on the response,
- `pred_err`: prediction error calculated as $y-y_{\text{hat}}$,
- `pred_err_sup`: upper limit of the $1-\alpha$ prediction interval on the prediction error,
- `pred_err_inf`: lower limit of the $1-\alpha$ prediction interval on the prediction error.

Author(s)

C. Capezza

References

Capezza C, Lepore A, Menafoglio A, Palumbo B, Vantini S. (2020) Control charts for monitoring ship operating conditions and CO₂ emissions based on scalar-on-function regression. *Applied Stochastic Models in Business and Industry*, 36(3):477–500. doi:10.1002/asmb.2507

Examples

```
library(funcharts)
air <- lapply(air, function(x) x[1:100, , drop = FALSE])
fun_covariates <- c("CO", "temperature")
mfdobj_x <- get_mfd_list(air[fun_covariates],
                       n_basis = 15,
                       lambda = 1e-2)
y <- rowMeans(air$NO2)
y1 <- y[1:80]
y2 <- y[81:100]
mfdobj_x1 <- mfdobj_x[1:80]
mfdobj_x2 <- mfdobj_x[81:100]
mod <- sof_pc(y1, mfdobj_x1)
cclist <- regr_cc_sof(object = mod,
                    y_new = y2,
                    mfdobj_x_new = mfdobj_x2)
plot_control_charts(cclist)
```

regr_cc_sof_real_time *Real-time Scalar-on-Function Regression Control Chart*

Description

This function builds a list of data frames, each of them is produced by `regr_cc_sof` and is needed to plot control charts for monitoring in real time a scalar quality characteristic adjusted for by the effect of multivariate functional covariates. The training data have already been used to fit the model. An additional tuning data set can be provided that is used to estimate the control chart limits. A phase II data set contains the observations to be monitored with the built control charts.

Usage

```

regr_cc_sof_real_time(
  mod_list,
  y_new,
  mfdobj_x_new_list,
  y_tuning = NULL,
  mfdobj_x_tuning_list = NULL,
  alpha = 0.05,
  parametric_limits = TRUE,
  include_covariates = FALSE,
  absolute_error = FALSE,
  ncores = 1
)

```

Arguments

- mod_list** A list of lists produced by [sof_pc_real_time](#), containing a list of scalar-on-function linear regression models estimated on functional data each evolving up to an intermediate domain point.
- y_new** A numeric vector containing the observations of the scalar response variable in the phase II monitoring data set.
- mfdobj_x_new_list** A list created using [get_mfd_df_real_time](#) or [get_mfd_list_real_time](#), denoting a list of functional data objects in the phase II monitoring data set, each evolving up to an intermediate domain point, with observations of the multivariate functional covariates. The length of this list and **mod_list** must be equal, and their elements in the same position in the list must correspond to the same intermediate domain point.
- y_tuning** An optional numeric vector containing the observations of the scalar response variable in the tuning data set. If `NULL`, the training data, i.e. the scalar response in **mod_list**, is also used as the tuning data set. Default is `NULL`.
- mfdobj_x_tuning_list** A list created using [get_mfd_df_real_time](#) or [get_mfd_list_real_time](#), denoting a list of functional data objects in the tuning data set (used to estimate control chart limits), each evolving up to an intermediate domain point, with observations of the multivariate functional covariates. The length of this list and **mod_list** must be equal, and their elements in the same position in the list must correspond to the same intermediate domain point. If `NULL`, the training data, i.e. the functional covariates in **mod_list**, are also used as the tuning data set. Default is `NULL`.
- alpha** See [regr_cc_sof](#).
- parametric_limits** See [regr_cc_sof](#).
- include_covariates** See [regr_cc_sof](#).
- absolute_error** See [regr_cc_sof](#).

`ncores` If you want parallelization, give the number of cores/threads to be used when creating objects separately for different instants.

Value

A list of data.frames each produced by `regr_cc_sof`, corresponding to a given instant.

See Also

[sof_pc_real_time](#), [regr_cc_sof](#)

Examples

```
library(funcharts)
data("air")
air1 <- lapply(air, function(x) x[1:8, , drop = FALSE])
air2 <- lapply(air, function(x) x[9:10, , drop = FALSE])
mfdobj_x1_list <- get_mfd_list_real_time(air1[c("CO", "temperature")],
                                       n_basis = 15,
                                       lambda = 1e-2,
                                       k_seq = c(0.5, 1))
mfdobj_x2_list <- get_mfd_list_real_time(air2[c("CO", "temperature")],
                                       n_basis = 15,
                                       lambda = 1e-2,
                                       k_seq = c(0.5, 1))
mfdobj_y1_list <- get_mfd_list_real_time(air1["NO2"],
                                       n_basis = 15,
                                       lambda = 1e-2,
                                       k_seq = c(0.5, 1))
mfdobj_y2_list <- get_mfd_list_real_time(air2["NO2"],
                                       n_basis = 15,
                                       lambda = 1e-2,
                                       k_seq = c(0.5, 1))
mod_list <- fof_pc_real_time(mfdobj_y1_list, mfdobj_x1_list)
cclist <- regr_cc_fof_real_time(
  mod_list = mod_list,
  mfdobj_y_new_list = mfdobj_y2_list,
  mfdobj_x_new_list = mfdobj_x2_list)
plot_control_charts_real_time(cclist, 1)
```

Description

It performs Phase I of the Robust Multivariate Functional Control Chart (RoMFCC) as proposed by Capezza et al. (2024).

Usage

```
RoMFCC_PhaseI(
  mfdobj,
  mfdobj_tuning = NULL,
  functional_filter_par = list(filter = TRUE),
  imputation_par = list(method_imputation = "RoMFDI"),
  pca_par = list(fev = 0.7),
  alpha = 0.05
)
```

Arguments

- | | |
|-----------------------|---|
| mfdobj | A multivariate functional data object of class mfd. A functional filter is applied to this data set, then flagged functional componentwise outliers are imputed in the robust imputation step. Finally robust multivariate functional principal component analysis is applied to the imputed data set for dimension reduction. |
| mfdobj_tuning | An additional functional data object of class mfd. After applying the filter and imputation steps on this data set, it is used to robustly estimate the distribution of the Hotelling's T2 and SPE statistics in order to calculate control limits to prevent overfitting issues that could reduce the monitoring performance of the RoMFCC. Default is NULL, but it is strongly recommended to use a tuning data set. |
| functional_filter_par | A list with an argument <code>filter</code> that can be TRUE or FALSE depending on if the functional filter step must be performed or not. All the other arguments of this list are passed as arguments to the function <code>functional_filter</code> in the filtering step. All the arguments that are not passed take their default values. See functional_filter for all the arguments and their default values. Default is <code>list(filter = TRUE)</code> . |
| imputation_par | A list with an argument <code>method_imputation</code> that can be "RoMFDI" or "mean" depending on if the imputation step must be done by means of RoMFDI or by just using the mean of each functional variable. If <code>method_imputation = "RoMFDI"</code> , all the other arguments of this list are passed as arguments to the function <code>RoMFDI</code> in the imputation step. All the arguments that are not passed take their default values. See RoMFDI for all the arguments and their default values. Default value is <code>list(method_imputation = "RoMFDI")</code> . |
| pca_par | A list with an argument <code>fev</code> , indicating a number between 0 and 1 denoting the fraction of variability that must be explained by the principal components to be selected in the RoMFPCA step. All the other arguments of this list are passed as arguments to the function <code>rpca_mfd</code> in the RoMFPCA step. All the arguments that are not passed take their default values. See rpca_mfd for all the arguments and their default values. Default value is <code>list(fev = 0.7)</code> . |
| alpha | The overall nominal type-I error probability used to set control chart limits. Default value is 0.05. |

Value

A list of the following elements that are needed in Phase II:

- T2 the Hotelling's T2 statistic values for the Phase I data set,
- SPE the SPE statistic values for the Phase I data set,
- T2_tun the Hotelling's T2 statistic values for the tuning data set,
- SPE_tun the SPE statistic values for the tuning data set,
- T2_lim the Phase II control limit of the Hotelling's T2 control chart,
- spe_lim the Phase II control limit of the SPE control chart,
- tuning TRUE if the tuning data set is provided, FALSE otherwise,
- mod_pca the final RoMFPCA model fitted on the Phase I data set,
- K = K the number of selected principal components,
- T_T2_inv if a tuning data set is provided, it returns the inverse of the covariance matrix of the first K scores, needed to calculate the Hotelling's T2 statistic for the Phase II observations.
- mean_scores_tuning_rob_mean if a tuning data set is provided, it returns the robust location estimate of the scores, needed to calculate the Hotelling's T2 and SPE statistics for the Phase II observations.

Author(s)

C. Capezza, F. Centofanti

References

Capezza, C., Centofanti, F., Lepore, A., Palumbo, B. (2024) Robust Multivariate Functional Control Charts. *Technometrics*, 66(4):531–547, doi:10.1080/00401706.2024.2327346.

Examples

```
## Not run:
library(funcharts)
mfdobj <- get_mfd_list(air, n_basis = 5)
nobs <- dim(mfdobj$coefs)[2]
set.seed(0)
ids <- sample(1:nobs)
mfdobj1 <- mfdobj[ids[1:100]]
mfdobj_tuning <- mfdobj[ids[101:300]]
mfdobj2 <- mfdobj[ids[-(1:300)]]
mod_phase1 <- RoMFCC_PhaseI(mfdobj = mfdobj1,
                           mfdobj_tuning = mfdobj_tuning)
phase2 <- RoMFCC_PhaseII(mfdobj_new = mfdobj2,
                        mod_phase1 = mod_phase1)
plot_control_charts(phase2)

## End(Not run)
```

Description

It calculates the Hotelling's and SPE monitoring statistics needed to plot the Robust Multivariate Functional Control Chart in Phase II.

Usage

```
RoMFCC_PhaseII(mfdoj_new, mod_phase1)
```

Arguments

- | | |
|-------------------------|---|
| <code>mfdoj_new</code> | A multivariate functional data object of class <code>mfd</code> , containing the Phase II observations to be monitored. |
| <code>mod_phase1</code> | Output obtained by applying the function <code>RoMFCC_PhaseI</code> to perform Phase I. See RoMFCC_PhaseI . |

Value

A `data.frame` with as many rows as the number of multivariate functional observations in the phase II data set and the following columns:

- one `id` column identifying the multivariate functional observation in the phase II data set,
- one `T2` column containing the Hotelling T2 statistic calculated for all observations,
- one column per each functional variable, containing its contribution to the T2 statistic,
- one `spe` column containing the SPE statistic calculated for all observations,
- `T2_lim` gives the upper control limit of the Hotelling's T2 control chart,
- `spe_lim` gives the upper control limit of the SPE control chart

Author(s)

C. Capezza, F. Centofanti

References

Capezza, C., Centofanti, F., Lepore, A., Palumbo, B. (2024) Robust Multivariate Functional Control Charts. *Technometrics*, 66(4):531–547, doi:10.1080/00401706.2024.2327346.

Examples

```
## Not run:
library(funcharts)
mfdobj <- get_mfd_list(air, n_basis = 5)
nobs <- dim(mfdobj$coeffs)[2]
set.seed(0)
ids <- sample(1:nobs)
mfdobj1 <- mfdobj[ids[1:100]]
mfdobj_tuning <- mfdobj[ids[101:300]]
mfdobj2 <- mfdobj[ids[-(1:300)]]
mod_phase1 <- RoMFCC_PhaseI(mfdobj = mfdobj1,
                           mfdobj_tuning = mfdobj_tuning)
phase2 <- RoMFCC_PhaseII(mfdobj_new = mfdobj2,
                        mod_phase1 = mod_phase1)
plot_control_charts(phase2)

## End(Not run)
```

RoMFDI

Robust Multivariate Functional Data Imputation (RoMFDI)

Description

It performs Robust Multivariate Functional Data Imputation (RoMFDI) as in Capezza et al. (2024).

Usage

```
RoMFDI(
  mfdobj,
  method_pca = "ROBPCA",
  fev = 0.999,
  n_dataset = 3,
  update = TRUE,
  niter_update = 10,
  alpha = 0.8
)
```

Arguments

| | |
|------------|---|
| mfdobj | A multivariate functional data object of class mfd. |
| method_pca | The method used in <code>rpca_mfd</code> to perform robust multivariate functional principal component analysis (RoMFPCA). See <code>rpca_mfd</code> . Default is "ROBPCA". |
| fev | Number between 0 and 1 denoting the proportion of variability that must be explained by the principal components to be selected for dimension reduction after applying RoMFPCA on the observed components to impute the missing ones. Default is 0.999. |

| | |
|--------------|--|
| n_dataset | To take into account the increased noise due to single imputation, the proposed RoMFDI allows multiple imputation. Due to the presence of the stochastic component in the imputation, it is worth explicitly noting that the imputed data set is not deterministically assigned. Therefore, by performing several times the RoMFDI in the imputation step of the RoMFCC implementation, the corresponding multiple estimated RoMFPCA models could be combined by averaging the robustly estimated covariance functions, thus performing a multiple imputation strategy as suggested by Van Ginkel et al. (2007). Default is 3. |
| update | The RoMFDI performs sequential imputation of missing functional components. If TRUE, Robust Multivariate Functional Principal Component Analysis (RoMFPCA) niter_update is updated times during the algorithm. If FALSE, the RoMFPCA used for imputation is always the same, i.e., the one performed on the original data sets containing only the observations with no missing functional components. Default is TRUE. |
| niter_update | The number of times the RoMFPCA is updated during the algorithm. It applies only if update is TRUE. Default value is 10. |
| alpha | This parameter measures the fraction of outliers the RoMFPCA algorithm should resist and is used only if method_pca is "ROBPCA". Default is 0.8. |

Value

A list with n_dataset elements. Each element is an mfd object containing mfdobj with stochastic imputation of the missing components.

Author(s)

C. Capezza, F. Centofanti

References

Capezza, C., Centofanti, F., Lepore, A., Palumbo, B. (2024) Robust Multivariate Functional Control Charts. *Technometrics*, 66(4):531–547, doi:10.1080/00401706.2024.2327346.

Van Ginkel, J. R., Van der Ark, L. A., Sijtsma, K., and Vermunt, J. K. (2007). Two-way imputation: a Bayesian method for estimating missing scores in tests and questionnaires, and an accurate approximation. *Computational Statistics & Data Analysis*, 51(8):4013—4027.

Examples

```
## Not run:
library(funcharts)
mfdobj <- get_mfd_list(air, grid = 1:24, n_basis = 13, lambda = 1e-2)
out <- functional_filter(mfdobj)
mfdobj_imp <- RoMFDI(out$mfdobj)

## End(Not run)
```

rpca_mfd

*Robust multivariate functional principal components analysis***Description**

It performs robust MFPCA as described in Capezza et al. (2024).

Usage

```
rpca_mfd(
  mfdobj,
  center = "fusem",
  scale = "funmad",
  nharm = 20,
  method = "ROBPCA",
  alpha = 0.8
)
```

Arguments

| | |
|--------|---|
| mfdobj | A multivariate functional data object of class mfd. |
| center | If TRUE, it centers the data before doing MFPCA with respect to the functional mean of the input data. If "fusem", it uses the functional M-estimator of location proposed by Centofanti et al. (2023) to center the data. Default is "fusem". |
| scale | If "funmad", it scales the data before doing MFPCA using the functional normalized median absolute deviation estimator proposed by Centofanti et al. (2023). If TRUE, it scales data using scale_mfd. Default is "funmad". |
| nharm | Number of multivariate functional principal components to be calculated. Default is 20. |
| method | If "ROBPCA", MFPCA uses ROBPCA of Hubert et al. (2005), as described in Capezza et al. (2024). If "Locantore", MFPCA uses the Spherical Principal Components procedure proposed by Locantore et al. (1999). If "Proj", MFPCA uses the Robust Principal Components based on Projection Pursuit algorithm of Croux and Ruiz-Gazen (2005). method If "normal", it uses pca_mfd on mfdobj. Default is "ROBPCA". |
| alpha | This parameter measures the fraction of outliers the algorithm should resist and is used only if method is "ROBPCA". Default is 0.8. |

Value

An object of pca_mfd class, as returned by the pca_mfd function when performing non robust multivariate functional principal component analysis.

Author(s)

C. Capezza, F. Centofanti

References

- Capezza, C., Centofanti, F., Lepore, A., Palumbo, B. (2024) Robust Multivariate Functional Control Charts. *Technometrics*, 66(4):531–547, doi:10.1080/00401706.2024.2327346.
- Centofanti, F., Colosimo, B.M., Grasso, M.L., Menafoglio, A., Palumbo, B., Vantini, S. (2023) Robust functional ANOVA with application to additive manufacturing. *Journal of the Royal Statistical Society Series C: Applied Statistics* 72(5), 1210–1234 doi:10.1093/jrsssc/qlad074
- Croux, C., Ruiz-Gazen, A. (2005). High breakdown estimators for principal components: The projection-pursuit approach revisited. *Journal of Multivariate Analysis*, 95, 206–226, doi:10.1016/j.jmva.2004.08.002.
- Hubert, M., Rousseeuw, P.J., Branden, K.V. (2005) ROBPCA: A New Approach to Robust Principal Component Analysis, *Technometrics* 47(1), 64–79, doi:10.1198/004017004000000563
- Locantore, N., Marron, J., Simpson, D., Tripoli, N., Zhang, J., Cohen K., K. (1999), Robust principal components for functional data. *Test*, 8, 1-28. doi:10.1007/BF02595862

Examples

```
library(funcharts)
dat <- simulate_mfd(nobs = 20, p = 1, correlation_type_x = "Bessel")
mfdobj <- get_mfd_list(dat$X_list, n_basis = 5)

# contaminate first observation
mfdobj$coefs[, 1, ] <- mfdobj$coefs[, 1, ] + 0.05

# plot_mfd(mfdobj) # plot functions to see the outlier
# pca <- pca_mfd(mfdobj) # non robust MFPCA
# rpca <- rpca_mfd(mfdobj) # robust MFPCA
# plot_pca_mfd(pca, harm = 1) # plot first eigenfunction, affected by outlier
# plot_pca_mfd(rpca, harm = 1) # plot first eigenfunction in robust case
```

scale_mfd

Standardize Multivariate Functional Data.

Description

Scale multivariate functional data contained in an object of class `mfd` by subtracting the mean function and dividing by the standard deviation function.

Usage

```
scale_mfd(mfdobj, center = TRUE, scale = TRUE)
```

Arguments

| | |
|--------|---|
| mfdobj | A multivariate functional data object of class mfd. |
| center | A logical value, or a fd object. When providing a logical value, if TRUE, mfdobj is centered, i.e. the functional mean function is calculated and subtracted from all observations in mfdobj, if FALSE, mfdobj is not centered. If center is a fd object, then this function is used as functional mean for centering. |
| scale | A logical value, or a fd object. When providing a logical value, if TRUE, mfdobj is scaled after possible centering, i.e. the functional standard deviation is calculated from all functional observations in mfdobj and then the observations are divided by this calculated standard deviation, if FALSE, mfdobj is not scaled. If scale is a fd object, then this function is used as standard deviation function for scaling. |

Details

This function has been written to work similarly as the function `scale` for matrices. When calculated, attributes `center` and `scale` are of class `fd` and have the same structure you get when you use `fda::mean.fd` and `fda::sd.fd`.

Value

A standardized object of class `mfd`, with two attributes, if calculated, `center` and `scale`, storing the mean and standard deviation functions used for standardization.

Examples

```
library(funcharts)
mfdobj <- data_sim_mfd()
mfdobj_scaled <- scale_mfd(mfdobj)
```

simulate_data_FRTM *Simulate data for real-time monitoring of univariate functional data*

Description

Generate synthetic data as in the simulation study of Centofanti et al. (2024).

Usage

```
simulate_data_FRTM(
  n_obs = 100,
  scenario = "1",
  shift = "IC",
  alignemnt_level = "M1",
  t_out_type = "0.3",
  severity = 0.5,
  grid = seq(0, 1, length.out = 100)
)
```

Arguments

| | |
|-----------------|---|
| n_obs | Number of curves generated. |
| scenario | A character string indicating the scenario considered. It could be "1", and "2". |
| shift | A character string indicating the shift considered. It could be "IC", in-control data, "OC_h", Shift A (Phase), "OC_x", Shift B (Amplitude) and "OC_xh", Shift C (Amplitude and Phase). |
| alignemnt_level | A character string indicating the alignment level considered. It could be "M1", "M2", and "M3". |
| t_out_type | If "0.3", change point at the 30% of the process. If "0.6", change point at the 60% of the process. |
| severity | Severity level. |
| grid | Grid of evaluation points. |

Value

A list containing the following arguments:

x_err: A list containing the discrete observations for each curve.

grid_i: A list of vector of time points where the curves are sampled.

h: A list containing the discrete observations of the warping function for each curve.

template: The discrete observations of the true template function.

grid_template: Time points where the template is sampled.

x_true: A list containing the discrete observations of the amplitude function for each curve.

grid: Grid of evaluation points.

out_control_t: Time of the change point.

References

Centofanti, F., A. Lepore, M. Kulahci, and M. P. Spooner (2024). Real-time monitoring of functional data. Accepted for publication in *Journal of Quality Technology*.

Examples

```
library(funcharts)
data<-simulate_data_FRTM(n_obs=20)
```

Description

Function used to simulate a data set to illustrate the use of funcharts. By default, it creates a data set with three functional covariates, a functional response generated as a function of the three functional covariates through a function-on-function linear model, and a scalar response generated as a function of the three functional covariates through a scalar-on-function linear model. This function covers the simulation study in Centofanti et al. (2021) for the function-on-function case and also simulates data in a similar way for the scalar response case. It is possible to select the number of functional covariates, the correlation function type for each functional covariate and the functional response, moreover it is possible to provide manually the mean and variance functions for both functional covariates and the response. In the default case, the function generates in-control data. Additional arguments can be used to generate additional data that are out of control, with mean shifts according to the scenarios proposed by Centofanti et al. (2021). Each simulated observation of a functional variable consists of a vector of discrete points equally spaced between 0 and 1 (by default 150 points), generated with noise.

Usage

```
simulate_mfd(  
  nobs = 1000,  
  p = 3,  
  R2 = 0.97,  
  shift_type_y = "0",  
  shift_type_x = c("0", "0", "0"),  
  correlation_type_y = "Bessel",  
  correlation_type_x = c("Bessel", "Gaussian", "Exponential"),  
  d_y = 0,  
  d_y_scalar = 0,  
  d_x = c(0, 0, 0),  
  n_comp_y = 10,  
  n_comp_x = 50,  
  P = 500,  
  ngrid = 150,  
  save_beta = FALSE,  
  mean_y = NULL,  
  mean_x = NULL,  
  variance_y = NULL,  
  variance_x = NULL,  
  sd_y = 0.3,  
  sd_x = c(0.3, 0.05, 0.3),  
  seed  
)
```

Arguments

| | |
|--------------------|--|
| nobs | The number of observation to simulate |
| p | The number of functional covariates to simulate. Default value is 3. |
| R2 | The desired coefficient of determination in the regression in both the scalar and functional response cases, Default is 0.97. |
| shift_type_y | The shift type for the functional response. There are five possibilities: "0" if there is no shift, "A", "B", "C" or "D" for the corresponding shift types shown in Centofanti et al. (2021). Default is "0". |
| shift_type_x | A list of length p, indicating, for each functional covariate, the shift type. For each element of the list, there are five possibilities: "0" if there is no shift, "A", "B", "C" or "D" for the corresponding shift types shown in Centofanti et al. (2021). By default, shift is not applied to any functional covariate. |
| correlation_type_y | A character vector indicating the type of correlation function for the functional response. See Centofanti et al. (2021) for more details. Three possible values are available, namely "Bessel", "Gaussian" and "Exponential". Default value is "Bessel". |
| correlation_type_x | A list of p character vectors indicating the type of correlation function for each functional covariate. See Centofanti et al. (2021) for more details. For each element of the list, three possible values are available, namely "Bessel", "Gaussian" and "Exponential". Default value is c("Bessel", "Gaussian", "Exponential"). |
| d_y | A number indicating the severity of the shift type for the functional response. Default is 0. |
| d_y_scalar | A number indicating the severity of the shift type for the scalar response. Default is 0. |
| d_x | A list of p numbers, each indicating the severity of the shift type for the corresponding functional covariate. By default, the severity is set to zero for all functional covariates. |
| n_comp_y | A positive integer number indicating how many principal components obtained after the eigendecomposition of the covariance function of the functional response variable to retain. Default value is 10. |
| n_comp_x | A positive integer number indicating how many principal components obtained after the eigendecomposition of the covariance function of the multivariate functional covariates variable to retain. Default value is 50. |
| P | A positive integer number indicating the number of equally spaced grid points over which the covariance functions are discretized. Default value is 500. |
| ngrid | A positive integer number indicating the number of equally spaced grid points between zero and one over which all functional observations are discretized before adding noise. Default value is 150. |
| save_beta | If TRUE, the true regression coefficients of both the function-on-function and the scalar-on-function models are saved. Default is FALSE. |

| | |
|------------|---|
| mean_y | The mean function of the functional response can be set manually through this argument. If not NULL, it must be a vector of length equal to ngrid, providing the values of the mean function of the functional response discretized on seq(0, 1, l=ngrid). If NULL, the mean function is generated as done in the simulation study of Centofanti et al. (2021). Default is NULL. |
| mean_x | The mean function of the functional covariates can be set manually through this argument. If not NULL, it must be a list of vectors, each with length equal to ngrid, providing the values of the mean function of each functional covariate discretized on seq(0, 1, l=ngrid). If NULL, the mean function is generated as done in the simulation study of Centofanti et al. (2021). Default is NULL. |
| variance_y | The variance function of the functional response can be set manually through this argument. If not NULL, it must be a vector of length equal to ngrid, providing the values of the variance function of the functional response discretized on seq(0, 1, l=ngrid). If NULL, the variance function is generated as done in the simulation study of Centofanti et al. (2021). Default is NULL. |
| variance_x | The variance function of the functional covariates can be set manually through this argument. If not NULL, it must be a list of vectors, each with length equal to ngrid, providing the values of the variance function of each functional covariate discretized on seq(0, 1, l=ngrid). If NULL, the variance function is generated as done in the simulation study of Centofanti et al. (2021). Default is NULL. |
| sd_y | A positive number indicating the standard deviation of the generated noise with which the functional response discretized values are observed. Default value is 0.3 |
| sd_x | A vector of p positive numbers indicating the standard deviation of the generated noise with which the functional covariates discretized values are observed. Default value is c(0.3, 0.05, 0.3). |
| seed | Deprecated: use set.seed() before calling the function for reproducibility. |

Value

A list with the following elements:

- X_list is a list of p matrices, each with dimension nobsxngrid, containing the simulated observations of the multivariate functional covariate
- Y is a nobsxngrid matrix with the simulated observations of the functional response
- y_scalar is a vector of length nobs with the simulated observations of the scalar response
- beta_fof, if save_beta = TRUE, is a list of p matrices, each with dimension P x P with the discretized functional coefficients of the function-on-function regression
- beta_sof, if save_beta = TRUE, is a list of p vectors, each with length P, with the discretized functional coefficients of the scalar-on-function regression

References

Centofanti F, Lepore A, Menafoglio A, Palumbo B, Vantini S. (2021) Functional Regression Control Chart. *Technometrics*, 63(3), 281–294. doi:10.1080/00401706.2020.1753581

| | |
|---------------|--|
| sim_funcharts | <i>Simulate example data for funcharts</i> |
|---------------|--|

Description

Function used to simulate three data sets to illustrate the use of funcharts. It uses the function `simulate_mfd`, which creates a data set with three functional covariates, a functional response generated as a function of the three functional covariates, and a scalar response generated as a function of the three functional covariates. This function generates three data sets, one for phase I, one for tuning, i.e., to estimate the control chart limits, and one for phase II monitoring. see also `simulate_mfd`.

Usage

```
sim_funcharts(nobs1 = 1000, nobs_tun = 1000, nobs2 = 60)
```

Arguments

| | |
|----------|---|
| nobs1 | The number of observation to simulate in phase I. Default is 1000. |
| nobs_tun | The number of observation to simulate the tuning data set. Default is 1000. |
| nobs2 | The number of observation to simulate in phase II. Default is 60. |

Value

A list with three objects, `datI` contains the phase I data, `datI_tun` contains the tuning data, `datII` contains the phase II data. In the phase II data, the first group of observations are in control, the second group of observations contains a moderate mean shift, while the third group of observations contains a severe mean shift. The shift types are described in the paper from Capezza et al. (2023).

References

Centofanti F, Lepore A, Menafoglio A, Palumbo B, Vantini S. (2021) Functional Regression Control Chart. *Technometrics*, 63(3), 281–294. doi:[10.1080/00401706.2020.1753581](https://doi.org/10.1080/00401706.2020.1753581)

Capezza, C., Centofanti, F., Lepore, A., Menafoglio, A., Palumbo, B., & Vantini, S. (2023). funcharts: Control charts for multivariate functional data in R. *Journal of Quality Technology*, 55(5), 566–583. doi:[10.1080/00224065.2023.2219012](https://doi.org/10.1080/00224065.2023.2219012)

sof_pc

*Scalar-on-function linear regression based on principal components***Description**

Scalar-on-function linear regression based on principal components. This function performs multivariate functional principal component analysis (MFPCA) to extract multivariate functional principal components from the multivariate functional covariates, then it builds a linear regression model of a scalar response variable on the covariate scores. Functional covariates are standardized before the regression. See Capezza et al. (2020) for additional details.

Usage

```
sof_pc(
  y,
  mfdobj_x,
  tot_variance_explained = 0.9,
  selection = "variance",
  single_min_variance_explained = 0,
  components = NULL
)
```

Arguments

| | |
|-------------------------------------|---|
| <code>y</code> | A numeric vector containing the observations of the scalar response variable. |
| <code>mfdobj_x</code> | A multivariate functional data object of class <code>mfd</code> denoting the functional covariates. |
| <code>tot_variance_explained</code> | The minimum fraction of variance that has to be explained by the set of multivariate functional principal components retained into the MFPCA model fitted on the functional covariates. Default is 0.9. |
| <code>selection</code> | A character value with one of three possible values: if "variance", the first M multivariate functional principal components are retained into the MFPCA model such that together they explain a fraction of variance greater than <code>tot_variance_explained</code> , if "PRESS", each j -th functional principal component is retained into the MFPCA model if, by adding it to the set of the first $j-1$ functional principal components, then the predicted residual error sum of squares (PRESS) statistic decreases, and at the same time the fraction of variance explained by that single component is greater than <code>single_min_variance_explained</code> . This criterion is used in Capezza et al. (2020). if "gcv", the criterion is equal as in the previous "PRESS" case, but the "PRESS" statistic is substituted by the generalized cross-validation (GCV) score. Default value is "variance". |

| | |
|-------------------------------|--|
| single_min_variance_explained | The minimum fraction of variance that has to be explained by each multivariate functional principal component into the MFPCA model fitted on the functional covariates such that it is retained into the MFPCA model. Default is 0. |
| components | A vector of integers with the components over which to project the functional covariates. If this is not NULL, the criteria to select components are ignored. If NULL, components are selected according to the criterion defined by selection. Default is NULL. |

Value

a list containing the following arguments:

- `mod`: an object of class `lm` that is a linear regression model where the scalar response variable is `y` and the covariates are the MFPCA scores of the functional covariates,
- `mod$coefficients` contains the matrix of coefficients of the functional regression basis functions,
- `pca`: an object of class `pca_mfd` obtained by doing MFPCA on the functional covariates,
- `beta_fd`: an object of class `mfd` object containing the functional regression coefficient $\beta(t)$ estimated with the scalar-on-function linear regression model,
- `components`: a vector of integers with the components selected in the `pca` model,
- `selection`: the same as the provided argument
- `single_min_variance_explained`: the same as the provided argument
- `tot_variance_explained`: the same as the provided argument
- `gcv`: a vector whose `j`-th element is the GCV score obtained when retaining the first `j` components in the MFPCA model.
- `PRESS`: a vector whose `j`-th element is the PRESS statistic obtained when retaining the first `j` components in the MFPCA model.

Author(s)

C. Capezza

References

Capezza C, Lepore A, Menafoglio A, Palumbo B, Vantini S. (2020) Control charts for monitoring ship operating conditions and CO2 emissions based on scalar-on-function regression. *Applied Stochastic Models in Business and Industry*, 36(3):477–500. doi:10.1002/asmb.2507

Examples

```
library(funcharts)
data("air")
air <- lapply(air, function(x) x[1:10, , drop = FALSE])
fun_covariates <- c("CO", "temperature")
mfdobj_x <- get_mfd_list(air[fun_covariates], lambda = 1e-2)
y <- rowMeans(air$NO2)
mod <- sof_pc(y, mfdobj_x)
```

| | |
|------------------|---|
| sof_pc_real_time | <i>Get a list of scalar-on-function linear regression models estimated on functional data each evolving up to an intermediate domain point.</i> |
|------------------|---|

Description

This function produces a list of objects, each of them contains the result of applying `sof_pc` to a scalar response variable and multivariate functional covariates evolved up to an intermediate domain point. See Capezza et al. (2020) for additional details on real-time monitoring.

Usage

```
sof_pc_real_time(
  y,
  mfd_real_time_list,
  single_min_variance_explained = 0,
  tot_variance_explained = 0.9,
  selection = "PRESS",
  components = NULL,
  ncores = 1
)
```

Arguments

| | |
|--|--|
| <code>y</code> | A numeric vector containing the observations of the scalar response variable. |
| <code>mfd_real_time_list</code> | A list created using <code>get_mfd_df_real_time</code> or <code>get_mfd_list_real_time</code> , denoting a list of functional data objects, each evolving up to an intermediate domain point, with observations of the multivariate functional covariates. |
| <code>single_min_variance_explained</code> | See <code>sof_pc</code> . |
| <code>tot_variance_explained</code> | See <code>sof_pc</code> . |
| <code>selection</code> | See <code>sof_pc</code> . |
| <code>components</code> | See <code>sof_pc</code> . |
| <code>ncores</code> | If you want parallelization, give the number of cores/threads to be used when creating objects separately for different instants. |

Value

A list of lists each produced by `sof_pc`, corresponding to a given instant.

Author(s)

C. Capezza

References

Capezza C, Lepore A, Menafoglio A, Palumbo B, Vantini S. (2020) Control charts for monitoring ship operating conditions and CO2 emissions based on scalar-on-function regression. *Applied Stochastic Models in Business and Industry*, 36(3):477–500. doi:10.1002/asmb.2507

See Also

[sof_pc](#), [get_mfd_df_real_time](#), [get_mfd_list_real_time](#)

Examples

```
library(funcharts)
data("air")
air <- lapply(air, function(x) x[1:10, , drop = FALSE])
mfdoobj_list <- get_mfd_list_real_time(air[c("CO", "temperature")],
                                     n_basis = 15,
                                     lambda = 1e-2,
                                     k_seq = c(0.5, 0.75, 1))

y <- rowMeans(air$NO2)
mod_list <- sof_pc_real_time(y, mfdoobj_list)
```

tensor_product_mfd *Tensor product of two Multivariate Functional Data objects*

Description

This function returns the tensor product of two Multivariate Functional Data objects. Each object must contain only one replication.

Usage

```
tensor_product_mfd(mfdoobj1, mfdoobj2 = NULL)
```

Arguments

| | |
|----------|---|
| mfdoobj1 | A multivariate functional data object, of class mfd, having only one functional observation. |
| mfdoobj2 | A multivariate functional data object, of class mfd, having only one functional observation. If NULL, it is set equal to mfdoobj1. Default is NULL. |

Value

An object of class bifd. If we denote with $x(s)=(x_1(s), \dots, x_p(s))$ the vector of p functions represented by mfdoobj1 and with $y(t)=(y_1(t), \dots, y_q(t))$ the vector of q functions represented by mfdoobj2, the output is the vector of pq bivariate functions

$f(s,t)=(x_1(s)y_1(t), \dots, x_1(s)y_q(t), \dots, x_p(s)y_1(t), \dots, x_p(s)y_q(t))$.

Examples

```
library(funcharts)
mfdoj1 <- data_sim_mfd(nobs = 1, nvar = 3)
mfdoj2 <- data_sim_mfd(nobs = 1, nvar = 2)
tensor_product_mfd(mfdoj1)
tensor_product_mfd(mfdoj1, mfdoj2)
```

which_ooc

Get the index of the out of control observations from control charts

Description

This function returns a list for each control chart and returns the id of all observations that are out of control in that control chart.

Usage

```
which_ooc(cclist)
```

Arguments

cclist A data.frame produced by [control_charts_sof_pc](#).

Value

A list of as many data.frame objects as the control charts in cclist. Each data frame has two columns, the n contains an index number giving the observation in the phase II data set, i.e. 1 for the first observation, 2 for the second, and so on, while the id column contains the id of the observation, which can be general and depends on the specific data set.

Examples

```
library(funcharts)
data("air")
air <- lapply(air, function(x) x[201:300, , drop = FALSE])
fun_covariates <- c("CO", "temperature")
mfdoj_x <- get_mfd_list(air[fun_covariates],
                      n_basis = 15,
                      lambda = 1e-2)

y <- rowMeans(air$NO2)
y1 <- y[1:60]
y_tuning <- y[61:90]
y2 <- y[91:100]
mfdoj_x1 <- mfdoj_x[1:60]
mfdoj_x_tuning <- mfdoj_x[61:90]
mfdoj_x2 <- mfdoj_x[91:100]
mod <- sof_pc(y1, mfdoj_x1)
cclist <- regr_cc_sof(object = mod,
```

```

y_new = y2,
mfdobj_x_new = mfdobj_x2,
y_tuning = y_tuning,
mfdobj_x_tuning = mfdobj_x_tuning,
include_covariates = TRUE)
which_ooc(cclist)

```

[.mfd

*Extract observations and/or variables from mfd objects.***Description**

Extract observations and/or variables from mfd objects.

Usage

```

## S3 method for class 'mfd'
mfdobj[i = TRUE, j = TRUE]

```

Arguments

| | |
|--------|---|
| mfdobj | An object of class mfd. |
| i | Index specifying functional observations to extract or replace. They can be numeric, character, or logical vectors or empty (missing) or NULL. Numeric values are coerced to integer as by <code>as.integer</code> (and hence truncated towards zero). They can also be negative integers, indicating functional observations to leave out of the selection. Logical vectors indicate TRUE for the observations to select. Character vectors will be matched to the argument <code>fdnames[[2]]</code> of <code>mfdobj</code> , i.e. to functional observations' names. |
| j | Index specifying functional variables to extract or replace. They can be numeric, logical, or character vectors or empty (missing) or NULL. Numeric values are coerced to integer as by <code>as.integer</code> (and hence truncated towards zero). They can also be negative integers, indicating functional variables to leave out of the selection. Logical vectors indicate TRUE for the variables to select. Character vectors will be matched to the argument <code>fdnames[[3]]</code> of <code>mfdobj</code> , i.e. to functional variables' names. |

Details

This function adapts the `fd::"[.fd"` function to be more robust and suitable for the `mfd` class. In fact, whatever the number of observations or variables you want to extract, it always returns a `mfd` object with a three-dimensional `coef` array. In other words, it behaves as you would always use the argument `drop=FALSE`. Moreover, you can extract observations and variables both by index numbers and by names, as you would normally do when using ``[`` with standard vector/matrices.

Value

a mfd object with selected observations and variables.

Examples

```
library(funcharts)
library(fda)

# In the following, we extract the first one/two observations/variables
# to see the difference with `[.fd`.
mfdobj <- data_sim_mfd()
fdobj <- fd(mfdobj$coefs, mfdobj$basis, mfdobj$fdnames)

# The argument `coef` in `fd`
# objects is converted to a matrix when possible.
dim(fdobj[1, 1]$coef)
# Not clear what is the second dimension:
# the number of replications or the number of variables?
dim(fdobj[1, 1:2]$coef)
dim(fdobj[1:2, 1]$coef)

# The argument `coef` in `mfd` objects is always a three-dimensional array.
dim(mfdobj[1, 1]$coef)
dim(mfdobj[1, 1:2]$coef)
dim(mfdobj[1:2, 1]$coef)

# Actually, `[.mfd` works as `[.fd` when passing also `drop = FALSE`
dim(fdobj[1, 1, drop = FALSE]$coef)
dim(fdobj[1, 1:2, drop = FALSE]$coef)
dim(fdobj[1:2, 1, drop = FALSE]$coef)
```


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