

Package ‘sde’

April 13, 2016

Type Package

Title Simulation and Inference for Stochastic Differential Equations

Version 2.0.15

Date 2016-04-13

Author Stefano Maria Iacus

Depends MASS, stats4, fda, zoo

Maintainer Stefano Maria Iacus <stefano.iacus@unimi.it>

Description Companion package to the book Simulation and Inference for Stochastic Differential Equations With R Examples, ISBN 978-0-387-75838-1, Springer, NY.

License GPL (>= 2)

NeedsCompilation yes

Repository CRAN

Date/Publication 2016-04-13 17:59:20

R topics documented:

BM	2
cpoint	3
DBridge	5
dcElerian	6
dcEuler	7
dcKessler	8
dcOzaki	9
dcShoji	10
dcSim	11
DWJ	12
EULERloglik	13
gmm	14
HPloglik	16
ksmooth	18
linear.mart.ef	20

MOdist	21
quotes	22
rcBS	23
rcCIR	24
rcOU	26
rsCIR	27
rsOU	28
sde.sim	29
sdeAIC	32
sdeDiv	34
SIMloglik	36
simple.ef	38
simple.ef2	40
Index	42

BM	<i>Brownian motion, Brownian bridge, and geometric Brownian motion simulators</i>
----	---

Description

Brownian motion, Brownian bridge, and geometric Brownian motion simulators.

Usage

```
BBridge(x=0, y=0, t0=0, T=1, N=100)
BM(x=0, t0=0, T=1, N=100)
GBM(x=1, r=0, sigma=1, T=1, N=100)
```

Arguments

x	initial value of the process at time t_0 .
y	terminal value of the process at time T .
t_0	initial time.
r	the interest rate of the GBM.
sigma	the volatility of the GBM.
T	final time.
N	number of intervals in which to split $[t_0, T]$.

Details

These functions return an invisible `ts` object containing a trajectory of the process calculated on a grid of $N+1$ equidistant points between t_0 and T ; i.e., $t[i] = t_0 + (T-t_0)*i/N$, i in $0:N$. $t_0=0$ for the geometric Brownian motion.

The function `BBridge` returns a trajectory of the Brownian bridge starting at x at time t_0 and ending at y at time T ; i.e.,

$$\{B(t), t_0 \leq t \leq T | B(t_0) = x, B(T) = y\}.$$

The function `BM` returns a trajectory of the translated Brownian motion $B(t), t \geq 0 | B(t_0) = x$; i.e., $x + B(t - t_0)$ for $t \geq t_0$. The standard Brownian motion is obtained choosing $x=0$ and $t_0=0$ (the default values).

The function `GBM` returns a trajectory of the geometric Brownian motion starting at x at time $t_0=0$; i.e., the process

$$S(t) = x \exp\{(r - \sigma^2/2)t + \sigma B(t)\}.$$

Value

`x` an invisible `ts` object

Author(s)

Stefano Maria Iacus

Examples

```
plot(BM())
plot(BBridge())
plot(GBM())
```

cpoint

Volatility change-point estimator for diffusion processes

Description

Volatility change-point estimator for diffusion processes based on least squares.

Usage

```
cpoint(x, mu, sigma)
```

Arguments

`x` a `ts` object.
`mu` a function of `x` describing the drift coefficient.
`sigma` a function of `x` describing the diffusion coefficient.

Details

The function returns a list of elements containing the discrete k_0 and continuous τ_0 change-point instant, the estimated volatilities before (θ_1) and after (θ_2) the time change. The model is assumed to be of the form

$$dX_t = b(X_t)dt + \theta\sigma(X_t)dW_t$$

where $\theta = \theta_1$ for $t \leq \tau_0$ and $\theta = \theta_2$ otherwise.

If the drift coefficient is unknown, the model

$$dX_t = b(X_t)dt + \theta dW_t$$

is considered and b is estimated nonparametrically.

Value

X a list

Author(s)

Stefano Maria Iacus

Examples

```
tau0 <- 0.6
k0 <- ceiling(1000*tau0)
set.seed(123)
X1 <- sde.sim(X0=1, N=2*k0, t0=0, T=tau0, model="CIR",
             theta=c(6,2,1))
X2 <- sde.sim(X0=X1[2*k0+1], N=2*(1000-k0), t0=tau0,
             T=1, model="CIR", theta=c(6,2,3))

Y <- ts(c(X1,X2[-1]), start=0, deltat=deltat(X1))
X <- window(Y,deltat=0.01)
DELTA <- deltat(X)
n <- length(X)

mu <- function(x) 6-2*x
sigma <- function(x) sqrt(x)

cp <- cpoint(X,mu,sigma)
cp
plot(X)
abline(v=tau0,lty=3)
abline(v=cp$tau0,col="red")

# nonparametric estimation
cpoint(X)
```

`DBridge`*Simulation of diffusion bridge*

Description

Simulation of diffusion bridge.

Usage

```
DBridge(x=0, y=0, t0=0, T=1, delta, drift, sigma, ...)
```

Arguments

<code>x</code>	initial value of the process at time <code>t0</code> .
<code>y</code>	terminal value of the process at time <code>T</code> .
<code>t0</code>	initial time.
<code>delta</code>	time step of the simulation.
<code>drift</code>	drift coefficient: an expression of two variables <code>t</code> and <code>x</code> .
<code>sigma</code>	diffusion coefficient: an expression of two variables <code>t</code> and <code>x</code> .
<code>T</code>	final time.
<code>...</code>	passed to the <code>sde.sim</code> function.

Details

The function returns a trajectory of the diffusion bridge starting at `x` at time `t0` and ending at `y` at time `T`.

The function uses the `sde.sim` function to simulate the paths internally. Refer to the `sde.sim` documentation for further information about the argument “...”

Value

`X` an invisible `ts` object

Author(s)

Stefano Maria Iacus

References

Bladt, M., Soerensen, M. (2007) Simple simulation of diffusion bridges with application to likelihood inference for diffusions, mimeo.

See Also

[sde.sim](#), [BBridge](#)

Examples

```
d <- expression((3-x))
s <- expression(1.2*sqrt(x))
par(mar=c(3,3,1,1))
par(mfrow=c(2,1))
set.seed(123)
X <- DBridge(x=1.7,y=0.5, delta=0.01, drift=d, sigma=s)
plot(X)
X <- DBridge(x=1,y=5, delta=0.01, drift=d, sigma=s)
plot(X)
```

dcElerian

Approximated conditional law of a diffusion process by Elerian's method

Description

Approximated conditional densities for $X(t)|X(t_0) = x_0$ of a diffusion process.

Usage

```
dcElerian(x, t, x0, t0, theta, d, s, sx, log=FALSE)
```

Arguments

x	vector of quantiles.
t	lag or time.
x0	the value of the process at time t0; see details.
t0	initial time.
theta	parameter of the process; see details.
log	logical; if TRUE, probabilities p are given as $\log(p)$.
d	drift coefficient as a function; see details.
s	diffusion coefficient as a function; see details.
sx	partial derivative w.r.t. x of the diffusion coefficient; see details.

Details

This function returns the value of the conditional density of $X(t)|X(t_0) = x_0$ at point x.

All the functions d, s, and sx must be functions of t, x, and theta.

Value

x a numeric vector

Author(s)

Stefano Maria Iacus

References

Elerian, O. (1998) A note on the existence of a closed form conditional density for the Milstein scheme, *Working Paper, Nuffield College, Oxford University*. Available at <http://www.nuff.ox.ac.uk/economics/papers/>

`dcEuler`*Approximated conditional law of a diffusion process*

Description

Approximated conditional densities for $X(t)|X(t_0) = x_0$ of a diffusion process.

Usage

```
dcEuler(x, t, x0, t0, theta, d, s, log=FALSE)
```

Arguments

<code>x</code>	vector of quantiles.
<code>t</code>	lag or time.
<code>x0</code>	the value of the process at time <code>t0</code> ; see details.
<code>t0</code>	initial time.
<code>theta</code>	parameter of the process; see details.
<code>log</code>	logical; if TRUE, probabilities p are given as $\log(p)$.
<code>d</code>	drift coefficient as a function; see details.
<code>s</code>	diffusion coefficient as a function; see details.

Details

This function returns the value of the conditional density of $X(t)|X(t_0) = x_0$ at point `x`.

The functions `d` and `s` must be functions of `t`, `x`, and `theta`.

Value

<code>x</code>	a numeric vector
----------------	------------------

Author(s)

Stefano Maria Iacus

dcKessler	<i>Approximated conditional law of a diffusion process by Kessler's method</i>
-----------	--

Description

Approximated conditional densities for $X(t)|X(t_0) = x_0$ of a diffusion process.

Usage

```
dcKessler(x, t, x0, t0, theta, d, dx, dxx, s, sx, sxx,
          log=FALSE)
```

Arguments

x	vector of quantiles.
t	lag or time.
x0	the value of the process at time t0; see details.
t0	initial time.
theta	parameter of the process; see details.
log	logical; if TRUE, probabilities p are given as $\log(p)$.
d	drift coefficient as a function; see details.
dx	partial derivative w.r.t. x of the drift coefficient; see details.
dxx	second partial derivative wrt x^2 of the drift coefficient; see details.
s	diffusion coefficient as a function; see details.
sx	partial derivative w.r.t. x of the diffusion coefficient; see details.
sxx	second partial derivative w.r.t. x^2 of the diffusion coefficient; see details.

Details

This function returns the value of the conditional density of $X(t)|X(t_0) = x_0$ at point x .

All the functions d , dx , dxx , s , sx , and sxx must be functions of t , x , and θ .

Value

x	a numeric vector
---	------------------

Author(s)

Stefano Maria Iacus

References

Kessler, M. (1997) Estimation of an ergodic diffusion from discrete observations, *Scand. J. Statist.*, 24, 211-229.

dcOzaki	<i>Approximated conditional law of a diffusion process by Ozaki's method</i>
---------	--

Description

Approximated conditional densities for $X(t)|X(t_0) = x_0$ of a diffusion process.

Usage

```
dcOzaki(x, t, x0, t0, theta, d, dx, s, log=FALSE)
```

Arguments

x	vector of quantiles.
t	lag or time.
x0	the value of the process at time t0; see details.
t0	initial time.
theta	parameter of the process; see details.
log	logical; if TRUE, probabilities p are given as $\log(p)$.
d	drift coefficient as a function; see details.
dx	partial derivative w.r.t. x of the drift coefficient; see details.
s	diffusion coefficient as a function; see details.

Details

This function returns the value of the conditional density of $X(t)|X(t_0) = x_0$ at point x.

All the functions d, dx, and s must be functions of t, x, and theta.

Value

x	a numeric vector
---	------------------

Author(s)

Stefano Maria Iacus

References

Ozaki, T. (1992) A bridge between nonlinear time series models and nonlinear stochastic dynamical systems: A local linearization approach, *Statistica Sinica*, 2, 25-83.

dcShoji *Approximated conditional law of a diffusion process by the Shoji-Ozaki method*

Description

Approximated conditional densities for $X(t)|X(t_0) = x_0$ of a diffusion process.

Usage

```
dcShoji(x, t, x0, t0, theta, d, dx, dxx, dt, s, log=FALSE)
```

Arguments

x	vector of quantiles.
t	lag or time.
x0	the value of the process at time t0; see details.
t0	initial time.
theta	parameter of the process; see details.
log	logical; if TRUE, probabilities p are given as $\log(p)$.
d	drift coefficient as a function; see details.
dx	partial derivative w.r.t. x of the drift coefficient; see details.
dxx	second partial derivative w.r.t. x ² of the drift coefficient; see details.
dt	partial derivative w.r.t. t of the drift coefficient; see details.
s	diffusion coefficient as a function; see details.

Details

This function returns the value of the conditional density of $X(t)|X(t_0) = x_0$ at point x.
All the functions d, dx, dxx, dt, and s must be functions of t, x, and theta.

Value

x a numeric vector

Author(s)

Stefano Maria Iacus

References

Shoji, L., Ozaki, T. (1998) Estimation for nonlinear stochastic differential equations by a local linearization method, *Stochastic Analysis and Applications*, 16, 733-752.

dcSim

Pedersen's simulated transition density

Description

Simulated transition density $X(t)|X(t_0) = x_0$ of a diffusion process based on Pedersen's method.

Usage

```
dcSim(x0, x, t, d, s, theta, M=10000, N=10, log=FALSE)
```

Arguments

<code>x0</code>	the value of the process at time θ .
<code>x</code>	value in which to evaluate the conditional density.
<code>t</code>	lag or time.
<code>theta</code>	parameter of the process; see details.
<code>log</code>	logical; if TRUE, probabilities p are given as $\log(p)$.
<code>d</code>	drift coefficient as a function; see details.
<code>s</code>	diffusion coefficient as a function; see details.
<code>N</code>	number of subintervals; see details.
<code>M</code>	number of Monte Carlo simulations, which should be an even number; see details.

Details

This function returns the value of the conditional density of $X(t)|X(0) = x_0$ at point x .

The functions `d` and `s`, must be functions of `t`, `x`, and `theta`.

Value

`x` a numeric vector

Author(s)

Stefano Maria Iacus

References

Pedersen, A. R. (1995) A new approach to maximum likelihood estimation for stochastic differential equations based on discrete observations, *Scand. J. Statist.*, 22, 55-71.

Examples

```

## Not run:
d1 <- function(t,x,theta) theta[1]*(theta[2]-x)
s1 <- function(t,x,theta) theta[3]*sqrt(x)

from <- 0.08
x <- seq(0,0.2, length=100)
sle10 <- NULL
sle2 <- NULL
sle5 <- NULL
true <- NULL
set.seed(123)
for(to in x){
  sle2 <- c(sle2, dcSim(from, to, 0.5, d1, s1,
    theta=c(2,0.02,0.15), M=50000,N=2))
  sle5 <- c(sle5, dcSim(from, to, 0.5, d1, s1,
    theta=c(2,0.02,0.15), M=50000,N=5))
  sle10 <- c(sle10, dcSim(from, to, 0.5, d1, s1,
    theta=c(2,0.02,0.15), M=50000,N=10))
  true <- c(true, dcCIR(to, 0.5, from, c(2*0.02,2,0.15)))
}

par(mar=c(5,5,1,1))
plot(x, true, type="l", ylab="conditional density")
lines(x, sle2, lty=4)
lines(x, sle5, lty=2)
lines(x, sle10, lty=3)
legend(0.15,20, legend=c("exact", "N=2", "N=5", "N=10"),
  lty=c(1,2,4,3))

## End(Not run)

```

 DWJ

Weekly closings of the Dow-Jones industrial average

Description

This dataset contains the weekly closings of the Dow-Jones industrial average in the period July 1971–August 1974. These data were proposed to test change-point estimators. There are 162 data, and the main evidence found by several authors is that a change in the variance occurred around the third week of March 1973.

Usage

```
data(DWJ)
```

References

Hsu, D.A. (1977) Tests for variance shift at an unknown time point, *Appl. Statist.*, 26(3), 279-284.

Hsu, D.A. (1979) Detecting shifts of parameter in gamma sequences with applications to stock price and air traffic flow analysis, *Journal American Stat. Ass.*, 74(365), 31-40.

Examples

```
data(DWJ)
ret <- diff(DWJ)/DWJ[-length(DWJ)]

par(mfrow=c(2,1))
par(mar=c(3,3,2,1))
plot(DWJ,main="Dow-Jones closings",ylab="",type="p")
plot(ret,main="Dow-Jones returns",ylab="",type="p")

cp <- cpoint(ret)
cp
abline(v=cp$tau0,lty=3)

cp <- cpoint(window(ret,end=cp$tau0))
cp
abline(v=cp$tau0,lty=3)
```

EULERloglik

Euler approximation of the likelihood

Description

Euler approximation of the likelihood of a process solution of a stochastic differential equation. These functions are useful to calculate approximated maximum likelihood estimators when the transition density of the process is not known.

Usage

```
EULERloglik(X, theta, d, s, log = TRUE)
```

Arguments

X	a ts object containing a sample path of an sde.
theta	vector of parameters.
d,s	drift and diffusion coefficients; see details.
log	logical; if TRUE, the log-likelihood is returned.

Details

The function EULERloglik returns the Euler approximation of the log-likelihood. The functions s and d are the drift and diffusion coefficients with arguments (t, x, theta).

Value

x a number

Author(s)

Stefano Maria Iacus

Examples

```
set.seed(123)
d <- expression(-1*x)
s <- expression(2)
sde.sim(drift=d, sigma=s) -> X

S <- function(t, x, theta) sqrt(theta[2])
B <- function(t, x, theta) -theta[1]*x

true.loglik <- function(theta){
  DELTA <- deltat(X)
  lik <- 0
  for(i in 2:length(X))
    lik <- lik + dnorm(X[i], mean=X[i-1]*exp(-theta[1]*DELTA),
      sd = sqrt((1-exp(-2*theta[1]*DELTA))*
        theta[2]/(2*theta[1])), TRUE)
  lik
}

xx <- seq(-3,3,length=100)
sapply(xx, function(x) true.loglik(c(x,4))) -> py
sapply(xx, function(x) EULERloglik(X,c(x,4),B,S)) -> pz

# true likelihood
plot(xx,py,type="l",xlab=expression(beta),ylab="log-likelihood")
lines(xx,pz, lty=2) # Euler
```

gmm

Generalized method of moments estimator

Description

Implementation of the estimator of the generalized method of moments by Hansen.

Usage

```
gmm(X, u, dim, guess, lower, upper, maxiter=30, tol1=1e-3,
  tol2=1e-3)
```

Arguments

X	a ts object containing a sample path of an sde.
u	a function of x, y, and theta and DELTA; see details.
dim	dimension of parameter space; see details.
guess	initial value of the parameters; see details.
lower	lower bounds for the parameters; see details.
upper	upper bounds for the parameters; see details.
tol1	tolerance for parameters; see details.
tol2	tolerance for Q1; see details.
maxiter	maximum number of iterations at the second stage; see details.

Details

The function `gmm` minimizes at the first stage the function $Q(\theta) = t(Gn(\theta)) * Gn(\theta)$ with respect to θ , where $Gn(\theta) = \text{mean}(u(X[i+1], X[i], \theta))$. Then a matrix of weights W is obtained by inverting an estimate of the long-run covariance and the quadratic function $Q1(\theta) = t(Gn(\theta)) * W * Gn(\theta)$ with starting value θ_1 (the solution at the first stage). The second stage is iterated until the first of these conditions verifies: (1) that the number of iterations reaches `maxiter`; (2) that the Euclidean distance between θ_1 and $\theta_2 < \text{tol1}$; (3) that $Q1 < \text{tol2}$.

The function `u` must be a function of $(u, y, \theta, \text{DELTA})$ and should return a vector of the same length as the dimension of the parameter space. The sanity checks are left to the user.

Value

`x` a list with parameter estimates, the value of $Q1$ at the minimum, and the Hessian

Author(s)

Stefano Maria Iacus

References

Hansen, L.P. (1982) Large Sample Properties of Generalized Method of Moments Estimators, *Econometrica*, 50(4), 1029-1054.

Examples

```
## Not run:
alpha <- 0.5
beta <- 0.2
sigma <- sqrt(0.05)
true <- c(alpha, beta, sigma)
names(true) <- c("alpha", "beta", "sigma")

x0 <- rsCIR(1, theta=true)
set.seed(123)
```

```

sde.sim(X0=x0,model="CIR",theta=true,N=500000,delta=0.001) -> X
X <- window(X, deltat=0.1)
DELTA = deltat(X)
n <- length(X)
X <- window(X, start=n*DELTA*0.5)
plot(X)

u <- function(x, y, theta, DELTA){
  c.mean <- theta[1]/theta[2] +
    (y-theta[1]/theta[2])*exp(-theta[2]*DELTA)
  c.var <- ((y*theta[3]^2 *
    (exp(-theta[2]*DELTA)-exp(-2*theta[2]*DELTA))/theta[2] +
    theta[1]*theta[3]^2*
    (1-exp(-2*theta[2]*DELTA))/(2*theta[2]^2)))
  cbind(x-c.mean,y*(x-c.mean), c.var-(x-c.mean)^2,
    y*(c.var-(x-c.mean)^2))
}

CIR.lik <- function(theta1,theta2,theta3) {
  n <- length(X)
  dt <- deltat(X)
  -sum(dcCIR(x=X[2:n], Dt=dt, x0=X[1:(n-1)],
    theta=c(theta1,theta2,theta3), log=TRUE))
}

fit <- mle(CIR.lik, start=list(theta1=.1, theta2=.1,theta3=.3),
  method="L-BFGS-B",lower=c(0.001,0.001,0.001), upper=c(1,1,1))
# maximum likelihood estimates
coef(fit)

gmm(X,u, guess=as.numeric(coef(fit)), lower=c(0,0,0),
  upper=c(1,1,1))

true

## End(Not run)

```

HPloglik

Ait-Sahalia Hermite polynomial expansion approximation of the likelihood

Description

Ait-Sahalia Hermite polynomial expansion and Euler approximation of the likelihood of a process solution of a stochastic differential equation. These functions are useful to calculate approximated maximum likelihood estimators when the transition density of the process is not known.

Usage

```
HPloglik(X, theta, M, F, s, log=TRUE)
```


Arguments

X	a ts object containing a sample path of an sde.
theta	vector of parameters.
M	list of derivatives; see details.
F	the transform function; see details.
s	drift and diffusion coefficient; see details.
log	logical; if TRUE, the log-likelihood is returned.

Details

The function HPloglik returns the Hermite polynomial approximation of the likelihood of a diffusion process transformed to have a unitary diffusion coefficient. The function F is the transform function, and s is the original diffusion coefficient. The list of functions M contains the transformed drift in M[[1]] and the subsequent six derivatives in x of M[[1]]. The functions F, s, and M have arguments (t, x, theta).

Value

x	a number
---	----------

Author(s)

Stefano Maria Iacus

References

Ait-Sahalia, Y. (1996) Testing Continuous-Time Models of the Spot Interest Rate, *Review of Financial Studies*, 9(2), 385-426.

Examples

```
set.seed(123)
d <- expression(-1*x)
s <- expression(2)
sde.sim(drift=d, sigma=s) -> X

M0 <- function(t, x, theta) -theta[1]*x
M1 <- function(t, x, theta) -theta[1]
M2 <- function(t, x, theta) 0
M3 <- function(t, x, theta) 0
M4 <- function(t, x, theta) 0
M5 <- function(t, x, theta) 0
M6 <- function(t, x, theta) 0
mu <- list(M0, M1, M2, M3, M4, M5, M6)

F <- function(t, x, theta) x/sqrt(theta[2])
S <- function(t, x, theta) sqrt(theta[2])

true.loglik <- function(theta) {
```

```

DELTA <- deltat(X)
lik <- 0
for(i in 2:length(X))
  lik <- lik + dnorm(X[i], mean=X[i-1]*exp(-theta[1]*DELTA),
    sd = sqrt((1-exp(-2*theta[1]*DELTA))*theta[2]/
      (2*theta[1])),TRUE)
  lik
}

xx <- seq(-3,3,length=100)
sapply(xx, function(x) HPloglik(X,c(x,4),mu,F,S)) -> px
sapply(xx, function(x) true.loglik(c(x,4))) -> py

plot(xx,px,type="l",xlab=expression(beta),ylab="log-likelihood")
lines(xx,py, lty=3) # true

```

ksmooth

*Nonparametric invariant density, drift, and diffusion coefficient estimation***Description**

Implementation of simple Nadaraya-Watson nonparametric estimation of drift and diffusion coefficient, and plain kernel density estimation of the invariant density for a one-dimensional diffusion process.

Usage

```

ksdrift(x, bw, n = 512)
ksdiff(x, bw, n = 512)
ksdens(x, bw, n = 512)

```

Arguments

x	a ts object.
bw	bandwidth.
n	number of points in which to calculate the estimates.

Details

These functions return the nonparametric estimate of the drift or diffusion coefficients for data x using the Nadaraya-Watson estimator for diffusion processes.

ksdens returns the density estimates of the invariant density.

If not provided, the bandwidth bw is calculated using Scott's rule (i.e., $bw = \text{len}^{(-1/5)} * \text{sd}(x)$) where $\text{len} = \text{length}(x)$ is the number of observed points of the diffusion path.

Value

val an invisible list of x and y coordinates and an object of class density in the case of invariant density estimation

Author(s)

Stefano Maria Iacus

References

Ait-Sahalia, Y. (1996) Nonparametric pricing of interest rate derivative securities, *Econometrica*, 64, 527-560.

Bandi, F., Phillips, P. (2003) Fully nonparametric estimation of scalar diffusion models, *Econometrica*, 71, 241-283.

Florens-Zmirou, D. (1993) On estimating the diffusion coefficient from discrete observations, *Journal of Applied Probability*, 30, 790-804.

Examples

```
set.seed(123)
theta <- c(6,2,1)
X <- sde.sim(X0 = rsCIR(1, theta), model="CIR", theta=theta,
            N=1000,delta=0.1)

b <- function(x)
  theta[1]-theta[2]*x

sigma <- function(x)
  theta[3]*sqrt(x)

minX <- min(X)
maxX <- max(X)

par(mfrow=c(3,1))
curve(b,minX,maxX)
lines(ksdrift(X),lty=3)

curve(sigma,minX, maxX)
lines(ksdiff(X),lty=3)

f <-function(x) dsCIR(x, theta)
curve(f,minX,maxX)
lines(ksdens(X),lty=3)
```

linear.mart.ef	<i>Linear martingale estimating function</i>
----------------	--

Description

Apply a linear martingale estimating function to find estimates of the parameters of a process solution of a stochastic differential equation.

Usage

```
linear.mart.ef(X, drift, sigma, a1, a2, guess, lower, upper,
              c.mean, c.var)
```

Arguments

X	a ts object containing a sample path of an sde.
drift	an expression for the drift coefficient; see details.
sigma	an expression for the diffusion coefficient; see details.
a1, a2	weights or instruments.
c.mean	expressions for the conditional mean.
c.var	expressions for the conditional variance.
guess	initial value of the parameters; see details.
lower	lower bounds for the parameters; see details.
upper	upper bounds for the parameters; see details.

Details

The function `linear.mart.ef` minimizes a linear martingale estimating function that is a particular case of the polynomial martingale estimating functions.

Value

x	a vector of estimates
---	-----------------------

Author(s)

Stefano Maria Iacus

References

Bibby, B., Soerensen, M. (1995) Martingale estimating functions for discretely observed diffusion processes, *Bernoulli*, 1, 17-39.

Examples

```

set.seed(123)
d <- expression(-1 * x)
s <- expression(1)
x0 <- rnorm(1, sd=sqrt(1/2))
sde.sim(X0=x0, drift=d, sigma=s, N=1000, delta=0.1) -> X

d <- expression(-theta * x)

linear.mart.ef(X, d, s, a1=expression(-x), lower=0, upper=Inf,
  c.mean=expression(x*exp(-theta*0.1)),
  c.var=expression((1-exp(-2*theta*0.1))/(2*theta)))

```

MOdist

*Markov Operator distance for clustering diffusion processes.***Description**

Markov Operator distance for clustering diffusion processes.

Usage

```
MOdist(x, M=50, rangeval=range(x), na.rm=TRUE, finite = TRUE))
```

Arguments

x	one or multi-dimensional time series.
M	number of splines bases used to approximate the Markov Operator.
rangeval	a vector containing lower and upper limit. Default is the range of x.

Details

This function return a lower triangular dist object to be further used in cluster analysis (see examples below).

If x is a one-dimensional time series, the output is the scalar 0, not a dist object.

If x has less than 2 observations, NA is returned.

If time series x contains missing data, then x is converted to a zoo object and missing data are imputed by interpolation.

Value

x	a dist object
---	---------------

Author(s)

Stefano Maria Iacus

References

De Gregorio, A. Iacus, S.M. (2008) Clustering of discretely observed diffusion processes, <http://arxiv.org/abs/0809.3902>

Examples

```
## Not run:
data(quotes)

plot(quotes)

d <- M0dist(quotes)
cl <- hclust( d )
groups <- cutree(cl, k=4)

cmd <- cmdscale(d)
plot( cmd, col=groups)
text( cmd, labels(d) , col=groups)

plot(quotes, col=groups)

plot(quotes, col=groups,ylim=range(quotes))

## End(Not run)
```

quotes	<i>Daily closings of 20 financial time series from 2006-01-03 to 2007-12-31</i>
--------	---

Description

This dataset contains the daily closings of 20 assets from NYSE/NASDAQ. Quotes from 2006-01-03 to 2007-12-31.

It is an object of class zoo. Original data contained missing data and interpolated. Used as example data to test the Markov Operator distance for discretely observed diffusion processes.

Usage

```
data(quotes)
```

References

De Gregorio, A. Iacus, S.M. (2008) Clustering of discretely observed diffusion processes, <http://arxiv.org/abs/0809.3902>

Examples

```

data(quotes)

plot(quotes)

d <- M0dist(quotes)
cl <- hclust( d )
groups <- cutree(cl, k=4)

cmd <- cmdscale(d)
plot( cmd, col=groups)
text( cmd, labels(d) , col=groups)

plot(quotes, col=groups)

plot(quotes, col=groups,ylim=range(quotes))

```

rcBS

Black-Scholes-Merton or geometric Brownian motion process conditional law

Description

Density, distribution function, quantile function, and random generation for the conditional law $X(t)|X(0) = x_0$ of the Black-Scholes-Merton process also known as the geometric Brownian motion process.

Usage

```

dcBS(x, Dt, x0, theta, log = FALSE)
pcBS(x, Dt, x0, theta, lower.tail = TRUE, log.p = FALSE)
qcBS(p, Dt, x0, theta, lower.tail = TRUE, log.p = FALSE)
rcBS(n=1, Dt, x0, theta)

```

Arguments

x	vector of quantiles.
p	vector of probabilities.
Dt	lag or time.
x0	the value of the process at time t; see details.
theta	parameter of the Black-Scholes-Merton process; see details.
n	number of random numbers to generate from the conditional distribution.
log, log.p	logical; if TRUE, probabilities p are given as $\log(p)$.
lower.tail	logical; if TRUE (default), probabilities are $P[X \leq x]$; otherwise, $P[X > x]$.

Details

This function returns quantities related to the conditional law of the process solution of

$$dX_t = \theta_1 X_t dt + \theta_2 X_t dW_t.$$

Constraints: $\theta_3 > 0$.

Value

x a numeric vector

Author(s)

Stefano Maria Iacus

References

Black, F., Scholes, M.S. (1973) The pricing of options and corporate liabilities, *Journal of Political Economy*, 81, 637-654.

Merton, R. C. (1973) Theory of rational option pricing, *Bell Journal of Economics and Management Science*, 4(1), 141-183.

Examples

```
rcBS(n=1, Dt=0.1, x0=1, theta=c(2,1))
```

rcCIR

Conditional law of the Cox-Ingersoll-Ross process

Description

Density, distribution function, quantile function and random generation for the conditional law $X(t + D_t) | X(t) = x_0$ of the Cox-Ingersoll-Ross process.

Usage

```
dcCIR(x, Dt, x0, theta, log = FALSE)
pcCIR(x, Dt, x0, theta, lower.tail = TRUE, log.p = FALSE)
qcCIR(p, Dt, x0, theta, lower.tail = TRUE, log.p = FALSE)
rcCIR(n=1, Dt, x0, theta)
```


Arguments

x	vector of quantiles.
p	vector of probabilities.
Dt	lag or time.
x0	the value of the process at time t; see details.
theta	parameter of the Ornstein-Uhlenbeck process; see details.
n	number of random numbers to generate from the conditional distribution.
log, log.p	logical; if TRUE, probabilities p are given as $\log(p)$.
lower.tail	logical; if TRUE (default), probabilities are $P[X \leq x]$; otherwise $P[X > x]$.

Details

This function returns quantities related to the conditional law of the process solution of

$$dX_t = (\theta_1 - \theta_2 X_t)dt + \theta_3 \sqrt{X_t} dW_t.$$

Constraints: $2\theta_1 > \theta_3^2$, all θ positive.

Value

x	a numeric vector
---	------------------

Author(s)

Stefano Maria Iacus

References

Cox, J.C., Ingersoll, J.E., Ross, S.A. (1985) A theory of the term structure of interest rates, *Econometrica*, 53, 385-408.

See Also

[rsCIR](#)

Examples

```
rcCIR(n=1, Dt=0.1, x0=1, theta=c(6,2,2))
```

rcOU

*Ornstein-Uhlenbeck or Vasicek process conditional law***Description**

Density, distribution function, quantile function, and random generation for the conditional law $X(t + D_t) | X(t) = x_0$ of the Ornstein-Uhlenbeck process, also known as the Vasicek process.

Usage

```
dcOU(x, Dt, x0, theta, log = FALSE)
pcOU(x, Dt, x0, theta, lower.tail = TRUE, log.p = FALSE)
qcOU(p, Dt, x0, theta, lower.tail = TRUE, log.p = FALSE)
rcOU(n=1, Dt, x0, theta)
```

Arguments

x	vector of quantiles.
p	vector of probabilities.
Dt	lag or time.
x0	the value of the process at time t; see details.
theta	parameter of the Ornstein-Uhlenbeck process; see details.
n	number of random numbers to generate from the conditional distribution.
log, log.p	logical; if TRUE, probabilities p are given as $\log(p)$.
lower.tail	logical; if TRUE (default), probabilities are $P[X \leq x]$; otherwise $P[X > x]$.

Details

This function returns quantities related to the conditional law of the process solution of

$$dX_t = (\theta_1 - \theta_2 X_t)dt + \theta_3 dW_t.$$

Constraints: $\theta_2 > 0, \theta_3 > 0$.

Please note that the process is stationary only if $\theta_2 > 0$.

Value

x	a numeric vector
---	------------------

Author(s)

Stefano Maria Iacus

References

Uhlenbeck, G. E., Ornstein, L. S. (1930) On the theory of Brownian motion, *Phys. Rev.*, 36, 823-841.

Vasicek, O. (1977) An Equilibrium Characterization of the Term Structure, *Journal of Financial Economics*, 5, 177-188.

See Also

[rsOU](#)

Examples

```
rcOU(n=1, Dt=0.1, x0=1, theta=c(0,2,1))
```

rsCIR

Cox-Ingersoll-Ross process stationary law

Description

Density, distribution function, quantile function, and random generation of the stationary law for the Cox-Ingersoll-Ross process.

Usage

```
dsCIR(x, theta, log = FALSE)
psCIR(x, theta, lower.tail = TRUE, log.p = FALSE)
qsCIR(p, theta, lower.tail = TRUE, log.p = FALSE)
rsCIR(n=1, theta)
```

Arguments

x	vector of quantiles.
p	vector of probabilities.
theta	parameter of the Cox-Ingersoll-Ross process; see details.
n	number of random numbers to generate from the conditional distribution.
log, log.p	logical; if TRUE, probabilities p are given as $\log(p)$.
lower.tail	logical; if TRUE (default), probabilities are $P[X \leq x]$; otherwise $P[X > x]$.

Details

This function returns quantities related to the stationary law of the process solution of

$$dX_t = (\theta_1 - \theta_2 X_t)dt + \theta_3 \sqrt{X_t}dW_t.$$

Constraints: $2\theta_1 > \theta_3^2$, all θ positive.

Value

x a numeric vector

Author(s)

Stefano Maria Iacus

References

Cox, J.C., Ingersoll, J.E., Ross, S.A. (1985) A theory of the term structure of interest rates, *Econometrica*, 53, 385-408.

See Also

[rsCIR](#)

Examples

```
rsCIR(n=1, theta=c(6,2,1))
```

rsOU

Ornstein-Uhlenbeck or Vasicek process stationary law

Description

Density, distribution function, quantile function, and random generation for the stationary law of the Ornstein-Uhlenbeck process also known as the Vasicek process.

Usage

```
dsOU(x, theta, log = FALSE)
psOU(x, theta, lower.tail = TRUE, log.p = FALSE)
qsOU(p, theta, lower.tail = TRUE, log.p = FALSE)
rsOU(n=1, theta)
```

Arguments

x vector of quantiles.
p vector of probabilities.
theta parameter of the Ornstein-Uhlenbeck process; see details.
n number of random numbers to generate from the conditional distribution.
log, log.p logical; if TRUE, probabilities p are given as $\log(p)$.
lower.tail logical; if TRUE (default), probabilities are $P[X \leq x]$; otherwise $P[X > x]$.

Details

This function returns quantities related to the stationary law of the process solution of

$$dX_t = (\theta_1 - \theta_2 X_t)dt + \theta_3 dW_t.$$

Constraints: $\theta_2 > 0, \theta_3 > 0$.

Please note that the process is stationary only if $\theta_2 > 0$.

Value

x a numeric vector

Author(s)

Stefano Maria Iacus

References

Uhlenbeck, G. E., Ornstein, L. S. (1930) On the theory of Brownian motion, *Phys. Rev.*, 36, 823-841.

Vasicek, O. (1977) An Equilibrium Characterization of the Term Structure, *Journal of Financial Economics*, 5, 177-188.

See Also

[rcOU](#)

Examples

```
rsOU(n=1, theta=c(0,2,1))
```

sde.sim

Simulation of stochastic differential equation

Description

Generic interface to different methods of simulation of solutions to stochastic differential equations.

Usage

```
sde.sim(t0 = 0, T = 1, X0 = 1, N = 100, delta, drift, sigma,
  drift.x, sigma.x, drift.xx, sigma.xx, drift.t,
  method = c("euler", "milstein", "KPS", "milstein2",
  "cdist", "ozaki", "shoji", "EA"),
  alpha = 0.5, eta = 0.5, pred.corr = T, rcdist = NULL,
  theta = NULL, model = c("CIR", "VAS", "OU", "BS"),
  k1, k2, phi, max.psi = 1000, rh, A, M=1)
```

Arguments

<code>t0</code>	time origin.
<code>T</code>	horizon of simulation.
<code>X0</code>	initial value of the process.
<code>N</code>	number of simulation steps.
<code>M</code>	number of trajectories.
<code>delta</code>	time step of the simulation.
<code>drift</code>	drift coefficient: an expression of two variables <code>t</code> and <code>x</code> .
<code>sigma</code>	diffusion coefficient: an expression of two variables <code>t</code> and <code>x</code> .
<code>drift.x</code>	partial derivative of the drift coefficient w.r.t. <code>x</code> : a function of two variables <code>t</code> and <code>x</code> .
<code>sigma.x</code>	partial derivative of the diffusion coefficient w.r.t. <code>x</code> : a function of two variables <code>t</code> and <code>x</code> .
<code>drift.xx</code>	second partial derivative of the drift coefficient w.r.t. <code>x</code> : a function of two variables <code>t</code> and <code>x</code> .
<code>sigma.xx</code>	second partial derivative of the diffusion coefficient w.r.t. <code>x</code> : a function of two variables <code>t</code> and <code>x</code> .
<code>drift.t</code>	partial derivative of the drift coefficient w.r.t. <code>t</code> : a function of two variables <code>t</code> and <code>x</code> .
<code>method</code>	method of simulation; see details.
<code>alpha</code>	weight <code>alpha</code> of the predictor-corrector scheme.
<code>eta</code>	weight <code>eta</code> of the predictor-corrector scheme.
<code>pred.corr</code>	boolean: whether to apply the predictor-correct adjustment; see details.
<code>rcdist</code>	a function that is a random number generator from the conditional distribution of the process; see details.
<code>theta</code>	vector of parameters for <code>cdist</code> ; see details.
<code>model</code>	model from which to simulate; see details.
<code>k1</code>	lower bound for <code>psi(x)</code> ; see details.
<code>k2</code>	upper bound for <code>psi(x)</code> ; see details.
<code>phi</code>	the function <code>psi(x) - k1</code> .
<code>max.psi</code>	upper value of the support of <code>psi</code> to search for its maximum.
<code>rh</code>	the rejection function; see details.
<code>A</code>	$A(x)$ is the integral of the <code>drift</code> between 0 and <code>x</code> .

Details

The function returns a `ts` object of length $N+1$; i.e., `X0` and the new N simulated values if $M=1$. For $M>1$, an `mts` (multidimensional `ts` object) is returned, which means that M independent trajectories are simulated. If the initial value `X0` is not of the length M , the values are recycled in order to have an initial vector of the correct length. If `delta` is not specified, then `delta` = $(T-t0)/N$. If `delta`

is specified, then N values of the solution of the sde are generated and the time horizon T is adjusted to be $N * \text{delta}$.

The function psi is $\text{psi}(x) = 0.5 * \text{drift}(x)^2 + 0.5 * \text{drift}.x(x)$.

If any of $\text{drift}.x$, $\text{drift}.xx$, $\text{drift}.t$, $\text{sigma}.x$, and $\text{sigma}.xx$ are not specified, then numerical derivation is attempted when needed.

If sigma is not specified, it is assumed to be the constant function 1.

The method of simulation can be one among: `euler`, `KPS`, `milstein`, `milstein2`, `cdist`, `EA`, `ozaki`, and `shoji`. No assumption on the coefficients or on `cdist` is checked: the user is responsible for using the right method for the process object of simulation.

The model is one among: `CIR`: Cox-Ingersoll-Ross, `VAS`: Vasicek, `OU` Ornstein-Uhlenbeck, `BS`: Black and Scholes. No assumption on the coefficient θ is checked: the user is responsible for using the right ones.

If the method is `cdist`, then the process is simulated according to its known conditional distribution. The random generator `rcdist` must be a function of n , the number of random numbers; dt , the time lag; x , the value of the process at time $t - dt$; and the vector of parameters θ .

For the exact algorithm method `EA`: if missing k_1 and k_2 as well as A , ρ and ϕ are calculated numerically by the function.

Value

`x` returns an invisible `ts` object

Author(s)

Stefano Maria Iacus

References

See Chapter 2 of the text.

Examples

```
# Ornstein-Uhlenbeck process
set.seed(123)
d <- expression(-5 * x)
s <- expression(3.5)
sde.sim(X0=10,drift=d, sigma=s) -> X
plot(X,main="Ornstein-Uhlenbeck")

# Multiple trajectories of the O-U process
set.seed(123)
sde.sim(X0=10,drift=d, sigma=s, M=3) -> X
plot(X,main="Multiple trajectories of O-U")

# Cox-Ingersoll-Ross process
# dXt = (6-3*Xt)*dt + 2*sqrt(Xt)*dWt
set.seed(123)
d <- expression( 6-3*x )
s <- expression( 2*sqrt(x) )
```

```

sde.sim(X0=10,drift=d, sigma=s) -> X
plot(X,main="Cox-Ingersoll-Ross")

# Cox-Ingersoll-Ross using the conditional distribution "rcCIR"

set.seed(123)
sde.sim(X0=10, theta=c(6, 3, 2), rcdist=rcCIR,
        method="cdist") -> X
plot(X, main="Cox-Ingersoll-Ross")

set.seed(123)
sde.sim(X0=10, theta=c(6, 3, 2), model="CIR") -> X
plot(X, main="Cox-Ingersoll-Ross")

# Exact simulation
set.seed(123)
d <- expression(sin(x))
d.x <- expression(cos(x))
A <- function(x) 1-cos(x)
sde.sim(method="EA", delta=1/20, X0=0, N=500,
        drift=d, drift.x = d.x, A=A) -> X
plot(X, main="Periodic drift")

```

sdeAIC

Akaike's information criterion for diffusion processes

Description

Implementation of the AIC statistics for diffusion processes.

Usage

```
sdeAIC(X, theta, b, s, b.x, s.x, s.xx, B, B.x, H, S, guess,
      ...)
```

Arguments

X	a ts object containing a sample path of an sde.
theta	a vector or estimates of the parameters.
b	drift coefficient of the model as a function of x and theta.
s	diffusion coefficient of the model as a function of x and theta.
b.x	partial derivative of b as a function of x and theta.
s.x	partial derivative of s as a function of x and theta.
s.xx	second-order partial derivative of s as a function of x and theta.
B	initial value of the parameters; see details.
B.x	partial derivative of B as a function of x and theta.

H	function of (x, y) , the integral of B/s ; optional.
S	function of (x, y) , the integral of $1/s$; optional.
guess	initial value for the parameters to be estimated; optional.
...	passed to the <code>optim</code> function; optional.

Details

The `sdeAIC` evaluates the AIC statistics for diffusion processes using Dacunha-Castelle and Florens-Zmirou approximations of the likelihood.

The parameter `theta` is supposed to be the value of the true MLE estimator or the minimum contrast estimator of the parameters in the model. If missing or `NULL` and `guess` is specified, `theta` is estimated using the minimum contrast estimator derived from the locally Gaussian approximation of the density. If both `theta` and `guess` are missing, nothing can be calculated.

If missing, B is calculated as $b/s - 0.5*s.x$ provided that $s.x$ is not missing.

If missing, $B.x$ is calculated as $b.x/s - b*s.x/(s^2) - 0.5*s.xx$, provided that $b.x$, $s.x$, and $s.xx$ are not missing.

If missing, both H and S are evaluated numerically.

Value

`x` the value of the AIC statistics

Author(s)

Stefano Maria Iacus

References

Dacunha-Castelle, D., Florens-Zmirou, D. (1986) Estimation of the coefficients of a diffusion from discrete observations, *Stochastics*, 19, 263-284.

Uchida, M., Yoshida, N. (2005) AIC for ergodic diffusion processes from discrete observations, preprint MHF 2005-12, march 2005, *Faculty of Mathematics, Kyushu University, Fukuoka, Japan*.

Examples

```
## Not run:
set.seed(123)
# true model generating data
dri <- expression(-(x-10))
dif <- expression(2*sqrt(x))
sde.sim(X0=10,drift=dri, sigma=dif,N=1000,delta=0.1) -> X

# we test the true model against two competing models
b <- function(x,theta) -theta[1]*(x-theta[2])
b.x <- function(x,theta) -theta[1]+0*x

s <- function(x,theta) theta[3]*sqrt(x)
s.x <- function(x,theta) theta[3]/(2*sqrt(x))
```

```

s.xx <- function(x,theta) -theta[3]/(4*x^1.5)
# AIC for the true model
sdeAIC(X, NULL, b, s, b.x, s.x, s.xx, guess=c(1,1,1),
       lower=rep(1e-3,3), method="L-BFGS-B")

s <- function(x,theta) sqrt(theta[3]**theta[4]*x)
s.x <- function(x,theta) theta[4]/(2*sqrt(theta[3]+theta[4]*x))
s.xx <- function(x,theta) -theta[4]^2/(4*(theta[3]+theta[4]*x)^1.5)
# AIC for competing model 1
sdeAIC(X, NULL, b, s, b.x, s.x, s.xx, guess=c(1,1,1,1),
       lower=rep(1e-3,4), method="L-BFGS-B")

s <- function(x,theta) (theta[3]+theta[4]*x)^theta[5]
s.x <- function(x,theta)
  theta[4]*theta[5]*(theta[3]+theta[4]*x)^(-1+theta[5])
s.xx <- function(x,theta) (theta[4]^2*theta[5]*(theta[5]-1)
  *(theta[3]+theta[4]*x)^(-2+theta[5]))
# AIC for competing model 2
sdeAIC(X, NULL, b, s, b.x, s.x, s.xx, guess=c(1,1,1,1,1),
       lower=rep(1e-3,5), method="L-BFGS-B")

## End(Not run)

```

sdeDiv

Phi-Divergences test for diffusion processes

Description

Phi-Divergences test for diffusion processes.

Usage

```
sdeDiv(X, theta1, theta0, phi= expression( -log(x) ), C.phi, K.phi,
      b, s, b.x, s.x, s.xx, B, B.x, H, S, guess, ...)
```

Arguments

X	a ts object containing a sample path of an sde.
theta1	a vector parameters for the hypothesis H1. If not given, theta1 is estimated from the data.
theta0	a vector parameters for the hypothesis H0.
phi	an expression containing the phi function of the phi-divergence.
C.phi	the value of first derivative of phi at point 1. If not given, it is calculated within this function.
K.phi	the value of second derivative of phi at point 1. If not given, it is calculated within this function.
b	drift coefficient of the model as a function of x and theta.

s	diffusion coefficient of the model as a function of x and theta.
b.x	partial derivative of b as a function of x and theta.
s.x	partial derivative of s as a function of x and theta.
s.xx	second-order partial derivative of s as a function of x and theta.
B	initial value of the parameters; see details.
B.x	partial derivative of B as a function of x and theta.
H	function of (x, y), the integral of B/s; optional.
S	function of (x, y), the integral of 1/s; optional.
guess	initial value for the parameters to be estimated; optional.
...	passed to the optim function; optional.

Details

The sdeDiv estimate the phi-divergence for diffusion processes defined as $D(\theta_1, \theta_0) = \int \phi(f(\theta_1)/f(\theta_0)) f(\theta_0)$ where f is the likelihood function of the process. This function uses the Dacunha-Castelle and Florens-Zmirou approximation of the likelihood for f .

The parameter θ_1 is supposed to be the value of the true MLE estimator or the minimum contrast estimator of the parameters in the model. If missing or NULL and guess is specified, θ_1 is estimated using the minimum contrast estimator derived from the locally Gaussian approximation of the density. If both θ_1 and guess are missing, nothing can be calculated.

The function always calculates the likelihood ratio test and the p-value of the test statistics. In some cases, the p-value of the phi-divergence test statistics is obtained by simulation. In such a case, the `out$est.pval` is set to TRUE

By default ϕ is set to $-\log(x)$. In this case the phi-divergence and the likelihood ratio test are equivalent (e.g. $\phi\text{-Div} = \text{LRT}/2$)

For more informations on phi-divergences for discretely observed diffusion processes see the references.

If missing, B is calculated as $b/s - 0.5*s.x$ provided that s.x is not missing.

If missing, B.x is calculated as $b.x/s - b*s.x/(s^2) - 0.5*s.xx$, provided that b.x, s.x, and s.xx are not missing.

If missing, both H and S are evaluated numerically.

Value

x a list containing the value of the divergence, its pvalue, the likelihood ratio test statistics and its p-value

Author(s)

Stefano Maria Iacus

References

Dacunha-Castelle, D., Florens-Zmirou, D. (1986) Estimation of the coefficients of a diffusion from discrete observations, *Stochastics*, 19, 263-284.

De Gregorio, A., Iacus, S.M. (2008) Divergences Test Statistics for Discretely Observed Diffusion Processes. Available at <http://arxiv.org/abs/0808.0853>

Examples

```
## Not run:
set.seed(123)
theta0 <- c(0.89218*0.09045,0.89218,sqrt(0.032742))
theta1 <- c(0.89218*0.09045/2,0.89218,sqrt(0.032742/2))

# we test the true model against two competing models
b <- function(x,theta) theta[1]-theta[2]*x
b.x <- function(x,theta) -theta[2]

s <- function(x,theta) theta[3]*sqrt(x)
s.x <- function(x,theta) theta[3]/(2*sqrt(x))
s.xx <- function(x,theta) -theta[3]/(4*x^1.5)

X <- sde.sim(X0=rsCIR(1, theta1), N=1000, delta=1e-3, model="CIR",
  theta=theta1)

sdeDiv(X=X, theta0 = theta0, b=b, s=s, b.x=b.x, s.x=s.x,
  s.xx=s.xx, method="L-BFGS-B",
  lower=rep(1e-3,3), guess=c(1,1,1))

sdeDiv(X=X, theta0 = theta1, b=b, s=s, b.x=b.x, s.x=s.x,
  s.xx=s.xx, method="L-BFGS-B",
  lower=rep(1e-3,3), guess=c(1,1,1))

lambda <- -1.75
myphi <- expression( (x^(lambda+1) -x - lambda*(x-1))/(lambda*(lambda+1)) )

sdeDiv(X=X, theta0 = theta0, phi = myphi, b=b, s=s, b.x=b.x,
  s.x=s.x, s.xx=s.xx, method="L-BFGS-B",
  lower=rep(1e-3,3), guess=c(1,1,1))

sdeDiv(X=X, theta0 = theta1, phi = myphi, b=b, s=s, b.x=b.x,
  s.x=s.x, s.xx=s.xx, method="L-BFGS-B",
  lower=rep(1e-3,3), guess=c(1,1,1))

## End(Not run)
```

Description

Pedersen's approximation of the likelihood of a process solution of a stochastic differential equation. This function is useful to calculate approximated maximum likelihood estimators when the transition density of the process is not known. It is computationally intensive.

Usage

```
SIMloglik(X, theta, d, s, M=10000, N=2, log=TRUE)
```

Arguments

X	a ts object containing a sample path of an sde.
theta	vector of parameters.
d, s	drift and diffusion coefficients; see details.
log	logical; if TRUE, the log-likelihood is returned.
N	number of subintervals; see details.
M	number of Monte Carlo simulations, which should be an even number; see details.

Details

The function SIMloglik returns the simulated log-likelihood obtained by Pedersen's method. The functions s and d are the drift and diffusion coefficients with arguments (t, x, theta).

Value

x	a number
---	----------

Author(s)

Stefano Maria Iacus

References

Pedersen, A. R. (1995) A new approach to maximum likelihood estimation for stochastic differential equations based on discrete observations, *Scand. J. Statist.*, 22, 55-71.

Examples

```
## Not run:
set.seed(123)
d <- expression(-1*x)
s <- expression(2)
sde.sim(drift=d, sigma=s, N=50, delta=0.01) -> X

S <- function(t, x, theta) sqrt(theta[2])
B <- function(t, x, theta) -theta[1]*x

true.loglik <- function(theta) {
```

```

DELTA <- deltat(X)
lik <- 0
for(i in 2:length(X))
  lik <- lik + dnorm(X[i], mean=X[i-1]*exp(-theta[1]*DELTA),
    sd = sqrt((1-exp(-2*theta[1]*DELTA))*
      theta[2]/(2*theta[1])),TRUE)
  lik
}

xx <- seq(-10,10,length=20)
sapply(xx, function(x) true.loglik(c(x,4))) -> py
sapply(xx, function(x) EULERloglik(X,c(x,4),B,S)) -> pz
sapply(xx, function(x) SIMloglik(X,c(x,4),B,S,M=10000,N=5)) -> pw

plot(xx,py,type="l",xlab=expression(beta),
  ylab="log-likelihood",ylim=c(0,15)) # true
lines(xx,pz, lty=2) # Euler
lines(xx,pw, lty=3) # Simulated

## End(Not run)

```

simple.ef

Simple estimating functions of types I and II

Description

Apply a simple estimating function to find estimates of the parameters of a process solution of a stochastic differential equation.

Usage

```
simple.ef(X, f, guess, lower, upper)
```

Arguments

X	a ts object containing a sample path of an sde.
f	a list of expressions of x and/or y and the parameters to be estimated; see details.
guess	initial value of the parameters; see details.
lower	lower bounds for the parameters; see details.
upper	upper bounds for the parameters; see details.

Details

The function `simple.ef` minimizes a simple estimating function of the form $\sum_i f_i(x, y; \theta) = 0$ or $\sum_i f_i(x; \theta)$ as a function of θ . The index i varies in $1:\text{length}(\theta)$.

The list `f` is a list of expressions in `x` or `(x, y)`.

Value

x a vector of estimates

Author(s)

Stefano Maria Iacus

References

Kessler, M. (1997) Estimation of an ergodic diffusion from discrete observations, *Scand. J. Statist.*, 24, 211-229.

Kessler, M. (2000) Simple and Explicit Estimating Functions for a Discretely Observed Diffusion Process, *Scand. J. Statist.*, 27, 65-82.

Examples

```
set.seed(123);
# Kessler's estimator for O-H process
K.est <- function(x) {
  n.obs <- length(x)
  n.obs/(2*(sum(x^2)))
}

# Least squares estimators for the O-H process
LS.est <- function(x) {
  n <- length(x) - 1
  k.sum <- sum(x[1:n]*x[2:(n+1)])
  dt <- deltat(x)
  ifelse(k.sum>0, -log(k.sum/sum(x[1:n]^2))/dt, NA)
}

d <- expression(-1 * x)
s <- expression(1)
x0 <- rnorm(1, sd=sqrt(1/2))
sde.sim(X0=x0, drift=d, sigma=s, N=2500, delta=0.1) -> X

# Kessler's estimator as estimating function
f <- list(expression(2*theta*x^2-1))
simple.ef(X, f, lower=0, upper=Inf)
K.est(X)

# Least Squares estimator as estimating function
f <- list(expression(x*(y-x*exp(-0.1*theta))))
simple.ef(X, f, lower=0, upper=Inf)
LS.est(X)
```

simple.ef2	<i>Simple estimating function based on the infinitesimal generator a the diffusion process</i>
------------	--

Description

Apply a simple estimating function based on the infinitesimal generator of a diffusion to find estimates of the parameters of a process solution of that particular stochastic differential equation.

Usage

```
simple.ef2(X, drift, sigma, h, h.x, h.xx, guess, lower,
          upper)
```

Arguments

X	a ts object containing a sample path of an sde.
drift	an expression for the drift coefficient; see details.
sigma	an expression for the diffusion coefficient; see details.
h	an expression of x and the parameters to be estimated; see details.
h.x	an expression of x containing the first derivative of h; see details.
h.xx	an expression of x containing the second derivative of h; see details.
guess	initial value of the parameters; see details.
lower	lower bounds for the parameters; see details.
upper	upper bounds for the parameters; see details.

Details

The function `simple.ef2` minimizes the simple estimating function of the form $\sum_i f_i(x; \theta) = 0$, where f is the result of applying the infinitesimal generator of the diffusion to the function h . This involves the drift and diffusion coefficients plus the first two derivatives of h . If not provided by the user, the derivatives are calculated by the function.

Value

x	a vector of estimates
---	-----------------------

Author(s)

Stefano Maria Iacus

References

Kessler, M. (1997) Estimation of an ergodic diffusion from discrete observations, *Scand. J. Statist.*, 24, 211-229.

Kessler, M. (2000) Simple and Explicit Estimating Functions for a Discretely Observed Diffusion Process, *Scand. J. Statist.*, 27, 65-82.

Examples

```
set.seed(123)
d <- expression(10 - x)
s <- expression(sqrt(x))
x0 <- 10
sde.sim(X0=x0,drift=d, sigma=s,N=1500,delta=0.1) -> X

# rather difficult problem unless a good initial guess is given
d <- expression(alpha + theta*x)
s <- expression(x^gamma)
h <- list(expression(x), expression(x^2), expression(x^2))
simple.ef2(X, d, s, h, lower=c(0,-Inf,0), upper=c(Inf,0,1))
```

Index

*Topic **datagen**

- BM, 2
- cpoint, 3
- DBridge, 5
- dcElerian, 6
- dcEuler, 7
- dcKessler, 8
- dcOzaki, 9
- dcShoji, 10
- dcSim, 11
- ksmooth, 18
- MOdist, 21
- rcBS, 23
- rcCIR, 24
- rcOU, 26
- rsCIR, 27
- rsOU, 28
- sde.sim, 29

*Topic **datasets**

- DWJ, 12
- quotes, 22

*Topic **ts**

- BM, 2
- cpoint, 3
- DBridge, 5
- dcElerian, 6
- dcEuler, 7
- dcKessler, 8
- dcOzaki, 9
- dcShoji, 10
- dcSim, 11
- EULERloglik, 13
- gmm, 14
- HPloglik, 16
- ksmooth, 18
- linear.mart.ef, 20
- MOdist, 21
- rcBS, 23
- rcCIR, 24

- rcOU, 26
- rsCIR, 27
- rsOU, 28
- sde.sim, 29
- sdeAIC, 32
- sdeDiv, 34
- SIMloglik, 36
- simple.ef, 38
- simple.ef2, 40

- BBridge, 5
- BBridge (BM), 2
- BM, 2

- cpoint, 3

- DBridge, 5
- dcBS (rcBS), 23
- dcCIR (rcCIR), 24
- dcElerian, 6
- dcEuler, 7
- dcKessler, 8
- dcOU (rcOU), 26
- dcOzaki, 9
- dcShoji, 10
- dcSim, 11
- dsCIR (rsCIR), 27
- dsOU (rsOU), 28
- DWJ, 12

- EULERloglik, 13

- GBM (BM), 2
- gmm, 14

- HPloglik, 16

- ksdens (ksmooth), 18
- ksdiff (ksmooth), 18
- ksdrift (ksmooth), 18
- ksmooth, 18

linear.mart.ef, 20

M0dist, 21

pcBS (rcBS), 23

pcCIR (rcCIR), 24

pcOU (rcOU), 26

psCIR (rsCIR), 27

psOU (rsOU), 28

qcBS (rcBS), 23

qcCIR (rcCIR), 24

qcOU (rcOU), 26

qsCIR (rsCIR), 27

qsOU (rsOU), 28

quotes, 22

rcBS, 23

rcCIR, 24

rcOU, 26, 29

rsCIR, 25, 27, 28

rsOU, 27, 28

sde.sim, 5, 29

sdeAIC, 32

sdeDiv, 34

SIMloglik, 36

simple.ef, 38

simple.ef2, 40