

Particle filters in the dynamichazard package

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This vignette covers the particle filter for the `dynamichazard` package in R. See <https://cran.r-project.org/web/packages/dynamichazard/vignettes/ddhazard.pdf> for more information on the package.

I assume that you are familiar with the setup in the `dynamichazard` package and the other estimation methods in the package. Further, some prior knowledge of particle filters is required. If you lack knowledge of particle filter then Doucet and Johansen (2009) provides a tutorial on particle filters and Kantas et al. (2015) covers parameter estimation with particle filters. This vignette relies heavily on Fearnhead et al. (2010).

1 Method

Model

The model is:

$$\begin{aligned} y_{it} &\sim P(y_{it} | \theta_{it}) \\ \theta_t &= \mathbf{X}_t \boldsymbol{\alpha}_t \\ \boldsymbol{\alpha}_t &= \mathbf{F} \boldsymbol{\alpha}_{t-1} + \mathbf{R} \boldsymbol{\eta}_t \quad \boldsymbol{\eta}_t \sim N(\mathbf{0}, \mathbf{Q}) \\ \boldsymbol{\alpha}_0 &\sim N(\mathbf{a}_0, \mathbf{Q}_0) \end{aligned} \tag{1}$$

where I denote the conditional densities as $\mathbf{y}_t \sim g(\cdot | \boldsymbol{\alpha}_t)$ and $\boldsymbol{\alpha}_t \sim f(\cdot | \boldsymbol{\alpha}_{t-1})$. We are in a survival analysis setting where the simplest model has an indicator of death of individual i in time t such that $y_{it} \in \{0, 1\}$ where θ_{it} is the linear predictor where we use the logistic function as the link function. For each $t = 1, \dots, d$, we have a risk set given by $R_t \subseteq \{1, 2, \dots, n\}$. The observed outcomes are denoted by $\mathbf{y}_t = \{y_{it}\}_{i \in R_t}$. \mathbf{X}_t is the matrix of the covariates and $\boldsymbol{\alpha}_t \in \mathbb{R}^p$ is the time-varying coefficients. The problems we are looking at have $n \gg p$ (e.g. $n = 100000$ and $p = 20$).

I will use a particle filter and smoother to get smoothed estimates of $\boldsymbol{\alpha}_1, \dots, \boldsymbol{\alpha}_d$ given the outcomes $\mathbf{y}_{1:d} = \{\mathbf{y}_1, \mathbf{y}_2, \dots, \mathbf{y}_d\}$ and use an EM-algorithm to estimate \mathbf{Q} and \mathbf{a}_0 . One choice of smoother is the generalized two-filter smoothing in Fearnhead et al. (2010) and Briers et al. (2010). I have included the $\mathcal{O}(N)$ smoother in Fearnhead et al. (2010) shown in algorithm 1. The rest of vignette is structured as follows: first I cover the particle filter and smoother. Then I cover the EM-algorithm and other miscellaneous topics. I will end with what is implemented at this point.

Considerations

Algorithm 1 shows the generalized two-filter smoother. It requires that we specify the following importance densities and re-sampling weights ("optimal" values are given as the right hand side):

$$\begin{aligned}
q\left(\boldsymbol{\alpha}_t \middle| \boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{y}_t\right) &= \mathrm{P}\left(\boldsymbol{\alpha}_t \middle| \boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{y}_t\right) \\
\beta_t^{(j)} &\propto \mathrm{P}\left(\mathbf{y}_t \middle| \boldsymbol{\alpha}_{t-1}^{(j)}\right) w_{t-1}^{(j)} \\
\tilde{q}\left(\boldsymbol{\alpha}_t \middle| \mathbf{y}_t, \tilde{\boldsymbol{\alpha}}_{t+1}^{(k)}\right) \tilde{\beta}_t^{(k)} &\approx \gamma_t\left(\boldsymbol{\alpha}_t\right) \mathrm{P}\left(\mathbf{y}_t \middle| \boldsymbol{\alpha}_t\right) \mathrm{P}\left(\tilde{\boldsymbol{\alpha}}_{t+1}^{(k)} \middle| \boldsymbol{\alpha}_t\right) \frac{\tilde{w}_{t+1}^{(k)}}{\gamma_{t+1}\left(\tilde{\boldsymbol{\alpha}}_{t+1}^{(k)}\right)} \\
\tilde{q}\left(\hat{\boldsymbol{\alpha}}_t^{(i)} \middle| \boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{y}_t, \tilde{\boldsymbol{\alpha}}_{t+1}^{(k)}\right) &= \mathrm{P}\left(\boldsymbol{\alpha}_t \middle| \boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{y}_t, \tilde{\boldsymbol{\alpha}}_{t+1}^{(k)}\right)
\end{aligned} \tag{2}$$

Further, we need to define a backwards filter distribution approximation:

$$\tilde{p}\left(\boldsymbol{\alpha}_t \middle| \mathbf{y}_{t:T}\right) \propto \gamma_t\left(\boldsymbol{\alpha}_t\right) \mathrm{P}\left(\mathbf{y}_{t:T} \middle| \boldsymbol{\alpha}_t\right) \tag{3}$$

with an artificial prior distribution $\gamma_t\left(\boldsymbol{\alpha}_t\right)$. See Briers et al. (2010) for how to select γ_t and examples hereof. Fearnhead et al. (2010) also provide examples.

Given the models of interest we have that:

- Evaluating $\mathrm{P}\left(\mathbf{y}_t \middle| \boldsymbol{\alpha}_t\right)$ is an expensive operation as $n \gg p$ and it has a $\mathcal{O}(np)$ computational cost. In general, any $\mathcal{O}(n)$ operation is going to take considerable time if it is needed in any steps of the algorithms.
- Evaluating $f\left(\boldsymbol{\alpha}_t \middle| \boldsymbol{\alpha}_{t-1}\right)$ and $f\left(\boldsymbol{\alpha}_t \middle| \boldsymbol{\alpha}_{t+1}\right)$ is cheap and can be done in closed form and sampling from these distribution can be done in closed form.
- The second example in Fearnhead et al. (2010) is close to the model here though with $n = 1$ and $p = 2$.

The following sections will closely follow the example shown in Fearnhead et al. (2010) and the appendix of the paper.

Forward filter (algorithm 2)

This section will cover some options for algorithm 2. Let $\mathcal{N}(\cdot|\cdot, \cdot)$ denote a multivariate normal distribution. We can select the proposal density as:

$$q\left(\boldsymbol{\alpha}_t \middle| \boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{y}_t\right) = \mathcal{N}\left(\boldsymbol{\alpha}_t \middle| \mathbf{F}\boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{Q}\right) \tag{4}$$

which we can sample from in $\mathcal{O}(Np^2)$ time if we have a pre-computed Cholesky decomposition of \mathbf{Q} . This is often called the *bootstrap filter*. Another option is to use normal approximation of \mathbf{y}_t 's conditional density:

$$\begin{aligned}
g(\mathbf{y}_t | \boldsymbol{\alpha}_t) &\simeq \tilde{g}_t(\mathbf{y}_t | \boldsymbol{\alpha}_t) \\
&= \mathcal{N}\left(\mathbf{X}_t \boldsymbol{\alpha}_t \middle| \mathbf{X}_t \mathbf{F} \bar{\boldsymbol{\alpha}}_{t-1} - \mathbf{G}_t (\mathbf{F} \bar{\boldsymbol{\alpha}}_{t-1})^{-1} \mathbf{g}_t (\mathbf{F} \bar{\boldsymbol{\alpha}}_{t-1}), -\mathbf{G}_t (\mathbf{F} \bar{\boldsymbol{\alpha}}_{t-1})^{-1}\right)
\end{aligned} \tag{5}$$

where:

$$\begin{aligned}
\mathbf{g}_t(\boldsymbol{\alpha}) &= \left\{ \frac{\partial \log P(y_{it} | \theta_{it})}{\partial \theta_{it}} \middle|_{\theta_{it} = \mathbf{x}_{it}^\top \boldsymbol{\alpha}} \right\}_{i \in R_t} \\
\mathbf{G}_t(\boldsymbol{\alpha}) &= \text{diag} \left(\left\{ \frac{\partial^2 \log P(y_{it} | \theta_{it})}{\partial \theta_{it}^2} \middle|_{\theta_{it} = \mathbf{x}_{it}^\top \boldsymbol{\alpha}} \right\}_{i \in R_t} \right)
\end{aligned} \tag{6}$$

to get:

$$q\left(\boldsymbol{\alpha}_t \middle| \boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{y}_t\right) \propto \mathcal{N}\left(\boldsymbol{\alpha}_t \middle| \mathbf{F} \boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{Q}\right) \tilde{g}\left(\mathbf{y}_t \middle| \mathbf{F} \boldsymbol{\alpha}_{t-1}^{(j)}\right) \tag{7}$$

Thus, we need to sample from:

$$\begin{aligned}
q\left(\boldsymbol{\alpha}_t \middle| \boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{y}_t\right) &= \mathcal{N}\left(\boldsymbol{\alpha}_t \middle| \boldsymbol{\mu}_t, \boldsymbol{\Sigma}_t\right) \\
\boldsymbol{\Sigma}_t^{-1} &= \mathbf{X}_t^\top (-\mathbf{G}_t (\mathbf{F} \bar{\boldsymbol{\alpha}}_{t-1})) \mathbf{X}_t + \mathbf{Q}^{-1} \\
\boldsymbol{\mu}_t &= \boldsymbol{\Sigma}_t \left(\mathbf{Q}^{-1} \mathbf{F} \boldsymbol{\alpha}_{t-1}^{(j)} + \mathbf{X}_t^\top (-\mathbf{G}_t (\mathbf{F} \bar{\boldsymbol{\alpha}}_{t-1})) \left(\mathbf{X}_t \mathbf{F} \bar{\boldsymbol{\alpha}}_{t-1} - \mathbf{G}_t (\mathbf{F} \bar{\boldsymbol{\alpha}}_{t-1})^{-1} \mathbf{g}_t (\mathbf{F} \bar{\boldsymbol{\alpha}}_{t-1}) \right) \right) \\
&= \boldsymbol{\Sigma}_t \left(\mathbf{Q}^{-1} \mathbf{F} \boldsymbol{\alpha}_{t-1}^{(j)} + \mathbf{X}_t^\top ((-\mathbf{G}_t (\mathbf{F} \bar{\boldsymbol{\alpha}}_{t-1})) \mathbf{X}_t \mathbf{F} \bar{\boldsymbol{\alpha}}_{t-1} + \mathbf{g}_t (\mathbf{F} \bar{\boldsymbol{\alpha}}_{t-1})) \right)
\end{aligned} \tag{8}$$

We can select $\bar{\boldsymbol{\alpha}}_{t-1}$ as the weighted mean given the particle cloud at time $t-1$ (that is, $\{\boldsymbol{\alpha}_{t-1}^{(1)}, \boldsymbol{\alpha}_{t-1}^{(2)}, \dots, \boldsymbol{\alpha}_{t-1}^{(N)}\}$). This is similar to the second order random walk example in Fearnhead et al. (2010). They use the mode which is feasible as the outcome only depends on one element of the state vector. The downside is an $\mathcal{O}(np^2 + p^3)$ computational cost though independent of the number of particles. The total cost of sampling is $\mathcal{O}(np^2 + p^3 + Np^2)$. Another option is to set $\bar{\boldsymbol{\alpha}}_{t-1} = \boldsymbol{\alpha}_{t-1}^{(j)}$ for each particle $j = 1, 2, \dots, N$ in the particle cloud at time $t-1$. This will improve the Taylor expansion but yields an $\mathcal{O}(N(np^2 + p^3))$ computational cost.

Next, we have the re-sampling weights. A simple solution is not to use an auxiliary particle filter as in the examples of Fearnhead et al. (2010) and set:

$$\beta_t^{(j)} \propto w_{t-1}^{(j)} \tag{9}$$

which has an $\mathcal{O}(N)$ cost of sampling. Another options is to set:

$$\begin{aligned}
\beta_t^{(j)} &\propto \mathbf{P} \left(\mathbf{y}_t \middle| \boldsymbol{\alpha}_{t-1}^{(j)} \right) w_{t-1}^{(j)} \\
&= w_{t-1}^{(j)} \int_{\boldsymbol{\alpha}_t} \mathcal{N} \left(\boldsymbol{\alpha}_t \middle| \mathbf{F} \boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{Q} \right) g \left(\mathbf{y}_t \middle| \boldsymbol{\alpha}_t \right) \partial \boldsymbol{\alpha}_t \\
&\approx w_{t-1}^{(j)} \int_{\boldsymbol{\alpha}_t} \mathcal{N} \left(\boldsymbol{\alpha}_t \middle| \mathbf{F} \boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{Q} \right) \tilde{g}_t \left(\mathbf{y}_t \middle| \boldsymbol{\alpha}_t \right) \partial \boldsymbol{\alpha}_t \\
&\approx \frac{w_{t-1}^{(j)} \mathcal{N} \left(\boldsymbol{\mu}_t \middle| \mathbf{F} \boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{Q} \right) \tilde{g}_t \left(\mathbf{y}_t \middle| \boldsymbol{\mu}_t \right)}{q \left(\boldsymbol{\mu}_t \middle| \boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{y}_t \right)}
\end{aligned} \tag{10}$$

This come at an $\mathcal{O}(Np^2)$ computational cost assuming that we are using (8) already. Otherwise it has the same computational cost as mentioned when I covered the importance density since we have to make the Taylor expansion approximation.

Backward filter (algorithm 3)

We need to specify the artificial prior $\gamma_t(\boldsymbol{\alpha}_t)$. Briers et al. (2010, page 69 and 70) provides recommendation on the selection. This leads to:

$$\begin{aligned}
\gamma_t(\boldsymbol{\alpha}_t) &= \mathcal{N} \left(\boldsymbol{\alpha}_t \middle| \overleftarrow{\mathbf{m}}_t, \overleftarrow{\mathbf{P}}_t \right) \\
\overleftarrow{\mathbf{m}}_t &= \mathbf{F}^t \mathbf{a}_0 \\
\overleftarrow{\mathbf{P}}_t &= \begin{cases} \mathbf{Q}_0 & t = 0 \\ \mathbf{F} \mathbf{P}_{t-1} \mathbf{F}^\top + \mathbf{Q} & t > 0 \end{cases}
\end{aligned} \tag{11}$$

Fearnhead et al. (2010) writes that then we end with:

$$\begin{aligned}
\mathbf{P}(\boldsymbol{\alpha}_t | \boldsymbol{\alpha}_{t+1}) &= \mathcal{N} \left(\boldsymbol{\alpha}_t \middle| \overleftarrow{\mathbf{a}}_t, \overleftarrow{\mathbf{S}}_t \right) \\
\overleftarrow{\mathbf{S}}_t &= \overleftarrow{\mathbf{P}}_t \mathbf{F}^\top \overleftarrow{\mathbf{P}}_{t+1}^{-1} \mathbf{Q} (\mathbf{F}^\top)^{-1} \\
\overleftarrow{\mathbf{a}}_t &= \overleftarrow{\mathbf{P}}_t \mathbf{F}^\top \overleftarrow{\mathbf{P}}_{t+1}^{-1} \boldsymbol{\alpha}_{t+1} + \overleftarrow{\mathbf{S}}_t \overleftarrow{\mathbf{P}}_t^{-1} \overleftarrow{\mathbf{m}}_t
\end{aligned} \tag{12}$$

which simplifies for the first order random walk to:

$$\begin{aligned}
\overleftarrow{\mathbf{m}}_t &= \mathbf{a}_0 \\
\overleftarrow{\mathbf{P}}_t &= t\mathbf{Q} + \mathbf{Q}_0 \\
\overleftarrow{\mathbf{S}}_t &= (t\mathbf{Q} + \mathbf{Q}_0) ((t+1)\mathbf{Q} + \mathbf{Q}_0)^{-1} \mathbf{Q} \\
\overleftarrow{\mathbf{a}}_t &= (t\mathbf{Q} + \mathbf{Q}_0) ((t+1)\mathbf{Q} + \mathbf{Q}_0)^{-1} \boldsymbol{\alpha}_{t+1} + \overleftarrow{\mathbf{S}}_t \overleftarrow{\mathbf{P}}_t^{-1} \overleftarrow{\mathbf{m}}_t
\end{aligned} \tag{13}$$

Further, setting $\mathbf{Q}_0 = \mathbf{Q}$ (only in the artificial prior where we may alter γ_0 – see Briers et al. (2010, page 70)) gives us:

$$\begin{aligned}\overleftarrow{\mathbf{S}}_t &= \mathbf{Q}^0 \\ \overleftarrow{\mathbf{a}}_t &= \mathbf{Q}^{-1}\alpha_{t+1} + \frac{1}{t+1}\mathbf{Q}^{-1}\mathbf{a}_0\end{aligned}\tag{14}$$

which makes no sense (assuming that I have not made an error) but this is what they write as the intermediate results in the appendix of Fearnhead et al. (2010). I figure the result should have been:

$$\begin{aligned}P(\alpha_t | \alpha_{t+1}) &= \mathcal{N}(\alpha_t | \overleftarrow{\mathbf{a}}_t, \overleftarrow{\mathbf{Z}}_t) \\ \overleftarrow{\mathbf{Z}}_t &= (\overleftarrow{\mathbf{P}}_t \mathbf{F}^\top \overleftarrow{\mathbf{P}}_{t+1}^{-1} + \overleftarrow{\mathbf{S}}_t \overleftarrow{\mathbf{P}}_t^{-1})^{-1} \\ \overleftarrow{\mathbf{a}}_t &= \overleftarrow{\mathbf{Z}}_t (\overleftarrow{\mathbf{P}}_t \mathbf{F}^\top \overleftarrow{\mathbf{P}}_{t+1}^{-1} \alpha_{t+1} + \overleftarrow{\mathbf{S}}_t \overleftarrow{\mathbf{P}}_t^{-1} \overleftarrow{\mathbf{m}}_t)\end{aligned}\tag{15}$$

such that the equivalent version of equation (14) is:

$$\begin{aligned}\overleftarrow{\mathbf{Z}}_t &= \left(\mathbf{Q}^{-1} + \frac{1}{t+1}\mathbf{Q}^{-1}\right)^{-1} \\ \overleftarrow{\mathbf{a}}_t &= \overleftarrow{\mathbf{Z}}_t \left(\mathbf{Q}^{-1}\alpha_{t+1} + \frac{1}{t+1}\mathbf{Q}^{-1}\mathbf{a}_0\right)\end{aligned}\tag{16}$$

The end results in the appendix of Fearnhead et al. (2010) make sense. This yields the following backward version of equation (8):

$$\begin{aligned}\tilde{q}(\alpha_t | \mathbf{y}_t, \tilde{\alpha}_{t+1}^{(k)}) &= \mathcal{N}(\alpha_t | \overleftarrow{\boldsymbol{\mu}}_t, \overleftarrow{\boldsymbol{\Sigma}}_t) \\ \overleftarrow{\boldsymbol{\Sigma}}_t^{-1} &= \mathbf{P}_t^{-1} + \mathbf{X}_t^\top (-\mathbf{G}_t (\mathbf{F}^{-1} \tilde{\alpha}_{t+1})) \mathbf{X}_t + \mathbf{F}^{-1} \mathbf{Q}^{-1} (\mathbf{F}^{-1})^\top \\ \overleftarrow{\boldsymbol{\mu}}_t &= \overleftarrow{\boldsymbol{\Sigma}}_t \left(\overleftarrow{\mathbf{P}}_t^{-1} \overleftarrow{\mathbf{m}}_t + \mathbf{F}^{-1} \mathbf{Q}^{-1} \tilde{\alpha}_{t+1}^{(k)} + \mathbf{X}_t^\top ((-\mathbf{G}_t (\mathbf{F}^{-1} \tilde{\alpha}_{t+1})) \mathbf{X}_t \mathbf{F}^{-1} \tilde{\alpha}_{t+1} + \mathbf{g}_t (\mathbf{F}^{-1} \tilde{\alpha}_{t+1})) \right)\end{aligned}\tag{17}$$

which is (/should be) an approximation of:

$$\begin{aligned}\tilde{q}(\alpha_t | \mathbf{y}_t, \tilde{\alpha}_{t+1}^{(k)}) &\propto g(\mathbf{y}_t | \alpha_t) f(\tilde{\alpha}_{t+1}^{(k)} | \alpha_t) \frac{\gamma_t(\alpha_t)}{\gamma_{t+1}(\tilde{\alpha}_{t+1}^{(k)})} \\ &\approx \tilde{g}(\mathbf{y}_t | \alpha_t) \mathcal{N}(\tilde{\alpha}_{t+1}^{(k)} | \mathbf{F}\alpha_t, \mathbf{Q}) \frac{\mathcal{N}(\alpha_t | \overleftarrow{\mathbf{m}}_t, \overleftarrow{\mathbf{P}}_t)}{\mathcal{N}(\tilde{\alpha}_{t+1}^{(k)} | \overleftarrow{\mathbf{m}}_{t+1}, \overleftarrow{\mathbf{P}}_{t+1})}\end{aligned}\tag{18}$$

The re-sampling weights can be computed similarly to the forward filter using the backward proposal density in equation (15) in the numerator for the backward transition density. We can also use a bootstrap like filter with the importance density by sampling from (15).

Combining / smoothing (algorithm 1)

We need to specify the importance density $\tilde{q}(\cdot | \boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{y}_t, \tilde{\boldsymbol{\alpha}}_{t+1}^{(k)})$ (see Fearnhead et al. (2010, page 453)). Again, we can use a similar idea to those in the appendix of Fearnhead et al. (2010) and choose:

$$\begin{aligned} \tilde{q}(\boldsymbol{\alpha}_t | \boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{y}_t, \tilde{\boldsymbol{\alpha}}_{t+1}^{(k)}) &= \mathcal{N}(\boldsymbol{\alpha}_t | \overleftarrow{\boldsymbol{\mu}}_t, \overleftarrow{\boldsymbol{\Sigma}}_t) \\ \overleftarrow{\boldsymbol{\Sigma}}_t^{-1} &= \mathbf{Q}^{-1} + \mathbf{X}_t^\top (-\mathbf{G}_t(\bar{\boldsymbol{\alpha}}_t)) \mathbf{X}_t + \mathbf{F}^{-1} \mathbf{Q}^{-1} (\mathbf{F}^{-1})^\top \\ \overleftarrow{\boldsymbol{\mu}}_t &= \overleftarrow{\boldsymbol{\Sigma}}_t \left(\mathbf{Q}^{-1} \boldsymbol{\alpha}_{t-1}^{(j)} + \mathbf{F}^{-1} \mathbf{Q}^{-1} \tilde{\boldsymbol{\alpha}}_{t+1}^{(k)} + \mathbf{X}_t^\top ((-\mathbf{G}_t(\bar{\boldsymbol{\alpha}}_t)) \mathbf{X}_t \bar{\boldsymbol{\alpha}}_t + \mathbf{g}_t(\bar{\boldsymbol{\alpha}}_t)) \right) \end{aligned} \quad (19)$$

where $\bar{\boldsymbol{\alpha}}_t$ can be a combined mean given the cloud means at time $t-1$ and $t+1$ or a mean for each of the two drawn particles in the (j_i, k_i) pairs. This is to approximate:

$$\tilde{q}(\boldsymbol{\alpha}_t | \boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{y}_t, \tilde{\boldsymbol{\alpha}}_{t+1}^{(k)}) \propto \tilde{g}(\mathbf{y}_t | \boldsymbol{\alpha}_t) f(\boldsymbol{\alpha}_t | \boldsymbol{\alpha}_{t-1}^{(j)}) \frac{f(\tilde{\boldsymbol{\alpha}}_{t+1}^{(k)} | \boldsymbol{\alpha}_t)}{\gamma_{t+1}(\tilde{\boldsymbol{\alpha}}_{t+1}^{(k)})} \quad (20)$$

We can also use a bootstrap like filter by sampling from:

$$\begin{aligned} \tilde{q}(\boldsymbol{\alpha}_t | \boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{y}_t, \tilde{\boldsymbol{\alpha}}_{t+1}^{(k)}) &= \mathcal{N}(\boldsymbol{\alpha}_t | \tilde{\mathbf{m}}, \tilde{\mathbf{S}}) \\ \tilde{\mathbf{S}} &= \left(\mathbf{Q}^{-1} + \mathbf{F}^{-1} \mathbf{Q}^{-1} (\mathbf{F}^{-1})^\top \right)^{-1} \\ \tilde{\mathbf{m}} &= \tilde{\mathbf{S}} \left(\mathbf{Q}^{-1} \mathbf{F} \boldsymbol{\alpha}_{t-1}^{(j)} + \mathbf{F}^{-1} \mathbf{Q}^{-1} \tilde{\boldsymbol{\alpha}}_{t+1}^{(k)} \right) \end{aligned} \quad (21)$$

Algorithm 1 $\mathcal{O}(N)$ generalized two filter smoother using the method in Fearnhead et al. (2010).

Input:

$\mathbf{Q}, \mathbf{Q}_0, \mathbf{a}_0, \mathbf{X}_1, \dots, \mathbf{X}_d, \mathbf{y}_1, \dots, \mathbf{y}_d, R_1, \dots, R_d, \mathbf{S}$

Importance density which optimally is (see Fearnhead et al. (2010, page 453)):

$$\tilde{q}(\boldsymbol{\alpha}_t | \boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{y}_t, \tilde{\boldsymbol{\alpha}}_{t+1}^{(k)}) = P(\boldsymbol{\alpha}_t | \boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{y}_t, \tilde{\boldsymbol{\alpha}}_{t+1}^{(k)}) \quad (22)$$

Let $\boldsymbol{\alpha}_t^{(i)}$ denote particle i at time t , $w_t^{(i)}$ denote the weight of the particle and $\beta_t^{(i)}$ denote the re-sampling weight.

1: **procedure** FILTER FORWARD

2: Run a forward particle filter to get a particle clouds

$\{\boldsymbol{\alpha}_t^{(j)}, w_t^{(j)}, \beta_{t+1}^{(j)}\}_{j=1, \dots, N}$ approximating $P(\boldsymbol{\alpha}_t | \mathbf{y}_{1:t})$ for $t = 0, 1, \dots, d$. See algorithm 2.

3: **procedure** FILTER BACKWARDS

4: Run a similar backward filter to get $\{\tilde{\boldsymbol{\alpha}}_t^{(k)}, \tilde{w}_t^{(k)}, \tilde{\beta}_{t-1}^{(k)}\}_{k=1, \dots, N}$ approximating $P(\boldsymbol{\alpha}_t | \mathbf{y}_{t:d})$ for $t = d+1, d, d-1, \dots, 1$. See algorithm 3.

5: **procedure** SMOOTH (COMBINE)

6: **for** $t = 1, \dots, d$ **do**

Re-sample:

7: $i = 1, 2, \dots, N_s$ pairs of (j_i, k_i) where each component is independently sampled using re-sampling weights $\beta_t^{(j)}$ and $\tilde{\beta}_t^{(k)}$.

Propagate:

8: Sample particles $\hat{\boldsymbol{\alpha}}_t^{(i)}$ from importance density $\tilde{q}(\cdot | \boldsymbol{\alpha}_{t-1}^{(j_i)}, \mathbf{y}_t, \tilde{\boldsymbol{\alpha}}_{t+1}^{(k_i)})$.

Re-weight:

9: Assign each particle weights:

$$\hat{w}_t^{(i)} \propto \frac{P(\hat{\boldsymbol{\alpha}}_t^{(i)} | \boldsymbol{\alpha}_{t-1}^{(j_i)}) P(\mathbf{y}_t | \hat{\boldsymbol{\alpha}}_t^{(i)}) P(\tilde{\boldsymbol{\alpha}}_{t+1}^{(k_i)} | \hat{\boldsymbol{\alpha}}_t^{(i)}) w_{t-1}^{(j_i)} \tilde{w}_{t+1}^{(k_i)}}{\tilde{q}(\hat{\boldsymbol{\alpha}}_t^{(i)} | \boldsymbol{\alpha}_{t-1}^{(j_i)}, \mathbf{y}_t, \tilde{\boldsymbol{\alpha}}_{t+1}^{(k_i)}) \beta_t^{(j_i)} \tilde{\beta}_t^{(k_i)} \gamma_{t+1}(\tilde{\boldsymbol{\alpha}}_{t+1}^{(k_i)})} \quad (23)$$

Algorithm 2 Forward filter due to Pitt and Shephard (1999). You can compare with Doucet and Johansen (2009, page 20 and 25). The version and notation below is from Fearnhead et al. (2010, page 449).

Input:

Importance density and specification of weights are optimally given by:

$$\begin{aligned} q\left(\boldsymbol{\alpha}_t \middle| \boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{y}_t\right) &= \mathrm{P}\left(\boldsymbol{\alpha}_t \middle| \boldsymbol{\alpha}_{t-1}^{(j)}, \mathbf{y}_t\right) \\ \beta_t^{(j)} &\propto \mathrm{P}\left(\mathbf{y}_t \middle| \boldsymbol{\alpha}_{t-1}^{(j)}\right) w_{t-1}^{(j)} \end{aligned} \quad (24)$$

- 1: Sample $\boldsymbol{\alpha}_0^{(1)}, \dots, \boldsymbol{\alpha}_0^{(N_f)}$ particles from $\mathcal{N}(\cdot | \mathbf{a}_0, \mathbf{Q}_0)$ and set the weights $w_0^{(1)}, \dots, w_0^{(N_f)}$ to $1/N_f$.
- 2: **for** $t = 1, \dots, d$ **do**
- 3: **procedure** RE-SAMPLE
- 4: Compute re-sampling weights $\beta_t^{(j)}$ and re-sample according to $\beta_t^{(j)}$ to get indices j_1, \dots, j_N .
- 5: **procedure** PROPAGATE
- 6: Sample new particles $\boldsymbol{\alpha}_t^{(i)}$ using importance density $q\left(\boldsymbol{\alpha}_t \middle| \boldsymbol{\alpha}_{t-1}^{(j_i)}, \mathbf{y}_t\right)$.
- 7: **procedure** RE-WEIGHT
- 8: Re-weight particles using:

$$w_t^{(i)} \propto \frac{\mathrm{P}\left(\mathbf{y}_t \middle| \boldsymbol{\alpha}_t^{(i)}\right) \mathrm{P}\left(\boldsymbol{\alpha}_t^{(i)} \middle| \boldsymbol{\alpha}_{t-1}^{(j_i)}\right) w_{t-1}^{(j_i)}}{q\left(\boldsymbol{\alpha}_t^{(i)} \middle| \boldsymbol{\alpha}_{t-1}^{(j_i)}, \mathbf{y}_t\right) \beta_t^{(j_i)}} \quad (25)$$

Algorithm 3 Backwards filter. See Briers et al. (2010) and Fearnhead et al. (2010).

Input:

A backwards filter distribution approximation:

$$\tilde{p}(\boldsymbol{\alpha}_t | \mathbf{y}_{t:T}) \propto \gamma_t(\boldsymbol{\alpha}_t) P(\mathbf{y}_{t:T} | \boldsymbol{\alpha}_t) \quad (26)$$

with an artificial prior distribution $\gamma_t(\boldsymbol{\alpha}_t)$. This is introduced as $P(\mathbf{y}_{t:T} | \boldsymbol{\alpha}_t)$ is not a density function in $\boldsymbol{\alpha}_t$.

Importance density and specification of weights (Fearnhead et al. (2010, page 451 – look in the example in the appendix)):

$$\tilde{q}(\boldsymbol{\alpha}_t | \mathbf{y}_t, \tilde{\boldsymbol{\alpha}}_{t+1}^{(k)}) \tilde{\beta}_t^{(k)} \approx \gamma_t(\boldsymbol{\alpha}_t) P(\mathbf{y}_t | \boldsymbol{\alpha}_t) P(\tilde{\boldsymbol{\alpha}}_{t+1}^{(k)} | \boldsymbol{\alpha}_t) \frac{\tilde{w}_{t+1}^{(k)}}{\gamma_{t+1}(\tilde{\boldsymbol{\alpha}}_{t+1}^{(k)})} \quad (27)$$

where we want (see Briers et al. (2010, page 74)):

$$\begin{aligned} \tilde{q}(\boldsymbol{\alpha}_t | \mathbf{y}_t, \tilde{\boldsymbol{\alpha}}_{t+1}^{(k)}) &\propto P(\mathbf{y}_t | \boldsymbol{\alpha}_t) P(\tilde{\boldsymbol{\alpha}}_{t+1}^{(k)} | \boldsymbol{\alpha}_t) \frac{\gamma_t(\boldsymbol{\alpha}_t)}{\gamma_{t+1}(\tilde{\boldsymbol{\alpha}}_{t+1}^{(k)})} \\ \tilde{\beta}_t^{(k)} &\propto \tilde{p}(\mathbf{y}_t | \tilde{\boldsymbol{\alpha}}_{t+1}^{(k)}) \tilde{w}_{t+1}^{(k)} \end{aligned} \quad (28)$$

- 1: Sample $\tilde{\boldsymbol{\alpha}}_{d+1}^{(1)}, \dots, \tilde{\boldsymbol{\alpha}}_{d+1}^{(N_f)}$ particles from $\gamma_{d+1}(\cdot)$ and set the weights $\tilde{w}_{d+1}^{(1)}, \dots, \tilde{w}_{d+1}^{(N_f)}$ to $1/N_f$.
- 2: **for** $t = d, \dots, 1$ **do**
- 3: **procedure** RE-SAMPLE
- 4: Compute re-sampling weights $\tilde{\beta}_t^{(k)}$ and re-sample according to $\tilde{\beta}_t^{(k)}$ to get indices k_1, \dots, k_N .
- 5: **procedure** PROPAGATE
- 6: Sample new particles $\tilde{\boldsymbol{\alpha}}_t^{(i)}$ using importance density $\tilde{q}(\boldsymbol{\alpha}_t | \tilde{\boldsymbol{\alpha}}_{t+1}^{(k_i)}, \mathbf{y}_t)$.
- 7: **procedure** RE-WEIGHT
- 8: Re-weight particles using (see Briers et al. (2010, page 72) and add the ratio of prior probability and re-sampling weight):

$$\tilde{w}_t^{(i)} \propto \frac{P(\mathbf{y}_t | \tilde{\boldsymbol{\alpha}}_t^{(i)}) P(\tilde{\boldsymbol{\alpha}}_{t+1}^{(k_i)} | \tilde{\boldsymbol{\alpha}}_t^{(i)}) \tilde{w}_{t+1}^{(k_i)} \gamma_t(\tilde{\boldsymbol{\alpha}}_t^{(i)})}{q(\tilde{\boldsymbol{\alpha}}_t^{(i)} | \tilde{\boldsymbol{\alpha}}_{t+1}^{(k_i)}, \mathbf{y}_t) \beta_t^{(k_i)} \gamma_{t+1}(\tilde{\boldsymbol{\alpha}}_{t+1}^{(k_i)})} \quad (29)$$

2 Log likelihood evaluation

We can evaluate the log likelihood for a particular value of $\theta = \{\mathbf{Q}, \mathbf{Q}_0, \mathbf{a}_0\}$ as described in Doucet and Johansen (2009, page 5) and Malik and Pitt (2011, page 193) using the forward particle filter shown in algorithm 2.

3 Parameter estimation

We can use the EM-algorithm (Dempster et al., 1977) to estimate \mathbf{Q} and \mathbf{a}_0 elements of $\theta = \{\mathbf{Q}, \mathbf{Q}_0, \mathbf{a}_0\}$. We do this by running algorithm 1 for the current θ . Then we compute the so-called *smoothed additive functional* or summary statistics:

$$\begin{aligned}
t_t^{(\theta)} &= \int_{\alpha_t} \alpha_t P_{\theta}(\alpha_t | \mathbf{y}_{1:d}) \partial \alpha_t \\
&\approx \sum_{i=1}^{N_s} \hat{\alpha}_t^{(i)} \hat{w}_t^{(i)} \approx \sum_{i=1}^{N_s} \alpha_t^{(j_i)} \hat{w}_{t+1}^{(i)} \approx \sum_{i=1}^{N_s} \tilde{\alpha}_t^{(k_i)} \hat{w}_{t-1}^{(i)} \\
T_t^{(\theta)} &= \int_{\alpha_{(t-1):t}} (\alpha_t - \mathbf{F}\alpha_{t-1}) (\alpha_t - \mathbf{F}\alpha_{t-1})^{\top} P_{\theta}(\alpha_{(t-1):t} | \mathbf{y}_{1:d}) \partial \alpha_{(t-1):t} \\
&\approx \sum_{i=1}^{N_s} \left(\hat{\alpha}_t^{(i)} - \mathbf{F}\alpha_{t-1}^{(j_i)} \right) \left(\hat{\alpha}_t^{(i)} - \mathbf{F}\alpha_{t-1}^{(j_i)} \right)^{\top} \hat{w}_t^{(i)} \\
&\approx \sum_{i=1}^{N_s} \left(\tilde{\alpha}_t^{(k_i)} - \mathbf{F}\hat{\alpha}_{t-1}^{(i)} \right) \left(\tilde{\alpha}_t^{(k_i)} - \mathbf{F}\hat{\alpha}_{t-1}^{(i)} \right)^{\top} \hat{w}_{t-1}^{(i)}
\end{aligned} \tag{30}$$

where $\alpha_{s:t} = \{\alpha_s, \alpha_{s+1}, \dots, \alpha_t\}$ and the subscript in P denotes that it is the probability given the parameter θ . I use that the normalized weights $\hat{w}_t^{(i)}$ and the pairs $\{\alpha_{t-1}^{(j_i)}, \hat{\alpha}_t^{(i)}, \tilde{\alpha}_{t+1}^{(k_i)}\}$ form a discrete approximation of $P_{\theta}(\alpha_{(t-1):(t+1)} | \mathbf{y}_{1:d})$. That is,

$$\begin{aligned}
P_{\theta}(\alpha_{(t-1):t+1} | \mathbf{y}_{1:d}) \\
\approx \sum_{i=1}^{N_s} \hat{w}_t^{(i)} \delta(\alpha_{t-1} - \alpha_{t-1}^{(j_i)}) \delta(\alpha_t - \hat{\alpha}_t^{(i)}) \delta(\alpha_{t+1} - \tilde{\alpha}_{t+1}^{(k_i)})
\end{aligned} \tag{31}$$

where $\delta(\cdot)$ is the Dirac delta function. The update of \mathbf{a}_0 and \mathbf{Q} given the summary statistics is:

$$\mathbf{a}_0 = t_0^{(\theta)} \quad \mathbf{Q} = \frac{1}{d} \sum_{t=1}^d \mathbf{R}^{\top} T_t^{(\theta)} \mathbf{R} \tag{32}$$

We then repeat with the new \mathbf{a}_0 and \mathbf{Q} for a given number of iterations or till a convergence criteria is satisfied. See Kantas et al. (2015), Del Moral et al. (2010) and Schön et al. (2011) for further details on parameter estimation with particle filters.

$$\begin{aligned}
P_{\theta}(\alpha_1, \alpha_0 | \mathbf{y}_{1:d}) &= P_{\theta}(\alpha_0 | \alpha_1, \mathbf{y}_{1:d}) P_{\theta}(\alpha_1 | \mathbf{y}_{1:d}) \\
&= \frac{P_{\theta}(\alpha_1, \mathbf{y}_{1:d} | \alpha_0) P_{\theta}(\alpha_0)}{P_{\theta}(\alpha_1, \mathbf{y}_{1:d})} P_{\theta}(\alpha_1 | \mathbf{y}_{1:d}) \\
&= \frac{P_{\theta}(\mathbf{y}_{1:d} | \alpha_1, \alpha_0) f_{\theta}(\alpha_1 | \alpha_0) P_{\theta}(\alpha_0)}{P_{\theta}(\alpha_1) P_{\theta}(\mathbf{y}_{1:d} | \alpha_1)} P_{\theta}(\alpha_1 | \mathbf{y}_{1:d}) \\
&= \frac{f_{\theta}(\alpha_1 | \alpha_0) P_{\theta}(\alpha_0)}{P_{\theta}(\alpha_1)} P_{\theta}(\alpha_1 | \mathbf{y}_{1:d}) \\
&= P_{\theta}(\alpha_0 | \alpha_1) P_{\theta}(\alpha_1 | \mathbf{y}_{1:d}) \\
&= \mathcal{N}(\alpha_0 | \mathbf{m}_{\theta}(\alpha_1), \mathbf{S}_{\theta}(\alpha_1)) P_{\theta}(\alpha_1 | \mathbf{y}_{1:d}) \\
&\approx \sum_{i=1}^{N_s} \mathcal{N}(\alpha_0 | \mathbf{m}_{\theta}(\hat{\alpha}_1^{(i)}), \mathbf{S}_{\theta}(\hat{\alpha}_1^{(i)})) \hat{w}_i^{(i)} \delta(\alpha_1 - \hat{\alpha}_1^{(i)})
\end{aligned} \tag{33}$$

where we use that $P_{\theta}(\mathbf{y}_{1:d} | \alpha_1, \alpha_0) = P_{\theta}(\mathbf{y}_{1:d} | \alpha_1)$ and have:

$$\begin{aligned}
\mathbf{S}_{\theta}(\alpha)^{-1} &= \mathbf{Q}_0^{-1} + \mathbf{F}^{-1} \mathbf{Q}^{-1} (\mathbf{F}^{-1})^{\top} \\
\mathbf{m}_{\theta}(\alpha) &= \mathbf{S}_{\theta}(\alpha) (\mathbf{Q}_0^{-1} \mathbf{a}_0 + \mathbf{F}^{-1} \mathbf{Q}^{-1} \mathbf{a}_0)
\end{aligned} \tag{34}$$

Thus, we end with:

$$\begin{aligned}
\mathbf{T}_1^{(\theta)} &\approx \sum_{i=1}^{N_s} \left(\hat{w}_1^{(i)} \hat{\alpha}_1^{(i)} (\hat{\alpha}_1^{(i)})^{\top} + \mathbf{F} \mathbf{Q}_0 \mathbf{F}^{\top} \right. \\
&\quad \left. - \hat{w}_1^{(i)} \mathbf{F} \mathbf{m}_{\theta}(\hat{\alpha}_1^{(i)}) (\hat{\alpha}_1^{(i)})^{\top} - \hat{w}_1^{(i)} \hat{\alpha}_1^{(i)} \mathbf{m}_{\theta}(\hat{\alpha}_1^{(i)})^{\top} \mathbf{F}^{\top} \right)
\end{aligned} \tag{35}$$

4 Implementation

The `PF_EM` method in the `dynamichazard` package contains an implementation of the above described method. You specify the number of particles by the `N_first`, `N_fw_n_bw` and `N_smooth` argument for respectively the N_f , N and $N_s > N$ as pointed out in the discussion in Fearnhead et al. (2010, page 460 and 461). Further, selecting $N_f > N$ may be preferable to ensure coverage of the state space at time 0 and $d + 1$.

The `method` argument specify how the filters are set up. The argument can take the following values:

- "bootstrap_filter" for a bootstrap filter.
- "PF_normal_approx_w_cloud_mean" and "AUX_normal_approx_w_cloud_mean" for the Taylor expansion of the conditional density of \mathbf{y}_t made around the weighted mean of the previous cloud. The PF and AUX prefix specifies whether or not the auxiliary version should be used.
- "PF_normal_approx_w_particles" and "AUX_normal_approx_w_particles" for the Taylor expansion of the conditional density of \mathbf{y}_t made around the parent (or/and child) particle. The PF_ and AUX_ prefix specifies whether or not the auxiliary version should be used.

The *Systematic Resampling* (Kitagawa, 1996) is used in all re-sampling steps. See Douc and Cappé (2005) for a comparison of re-sampling methods. The rest of the arguments to PF_EM are similar to those of the `ddhazard` function.

5 Other options

The $\mathcal{O}(N^2)$ two-filter smoother in Fearnhead et al. (2010) is going to be computationally expensive as an approximation is going to be needed for equation (8) in the article. For instance, only the Taylor expansion approximation around a single point to approximate g would be feasible. The non-auxiliary version in Briers et al. (2010) is more feasible as it only requires evaluation of f in the smoothing part of two-filter smoother (see equation (46) in the paper). Similar conclusions applies to the forward smoother in Del Moral et al. (2010) and the backward smoother as presented in Kantas et al. (2015). Both have a $\mathcal{O}(N^2)$ computational cost.

Despite the $\mathcal{O}(N^2)$ cost of the method in Briers et al. (2010) and Del Moral et al. (2010) they are still worthy candidates as the computational cost is independent of the number of observations, n . Further, the computational cost can be reduced to $\mathcal{O}(N \log(N))$ with the approximations in Klaas et al. (2006).

The method in Malik and Pitt (2011, see particularly section 6.2 on page 203) can be used to do continuous likelihood evaluation. I am not sure how well these method scale with higher state dimension, p .

Kantas et al. (2015) show empirically that it may be worth just using a forward filter. However, the example is with a univariate outcome ($n = 1$ – not to be confused with the number of periods d). The cost here of the forward filter is at least $\mathcal{O}(dNnp)$. Every new particle yields an $\mathcal{O}(dnp)$ cost which is expensive due to the large number of outcomes n . Thus, the considerations are different and a $\mathcal{O}(dNnp + N^2)$ method will not make a big difference unless N is large.

An alternative is to add noise to $\boldsymbol{\theta}_t$ and use the methods in Andrieu and Doucet (2002).

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