Partie V
Annexes

Annexe A
Approximation d'une fonction non linéaire par une population de fonctions linéaires locales

Cette annexe est un résumé synthétique du principe d'approximation par population de fonctions linéaires locales. La motivation de cette méthode est l'approximation d'une fonction multidimensionnelle non linéaire $y = f(e)$ de $\Re^N$ vers $\Re^m$ ($e = [e_1, e_2, e_3, ..., e_N]$ constituant le vecteur des entrées de f et $y = [y_1, y_2, y_3, ..., y_m]$ le vecteur des sorties de f) par un filtre adaptatif Ψ fournissant une approximation $\hat{f}(e)$ de cette fonction. Il est possible de réaliser une approximation de f à l'aide de k fonctions à bases radiales échantillonnant l'espace des entrées de f. Dans ce cas, l'approximation est donnée par la relation

$$\hat{f}(e) = \Psi(e, W) = W \cdot g(e) \tag{A.1}$$

où W et $g(e)$ représentent respectivement la matrice à m lignes et k colonnes des paramètres (ou «poids») de Ψ et $g(e)$ le vecteur à k lignes des valeurs des fonctions à base radiale lorsque l'entrée est égale à e ($g(e) = [g_1(e), g_2(e), g_3(e), ..., g_k(e)]$). Chacune des fonctions à base radiale est de même dimension que l'espace de départ de $f(e)$. Le pavage de cette espace peut poser problème lorsque la dimension du vecteur des entrées est élevée. Remarquons cependant que la fonction $f(e)$ peut être linéaire ou approximativement linéaire pour un sous-ensemble des variables considérées. Par exemple, le système monodimensionnel dont le comportement est décrit par l'équation

$$\ddot{x} = \alpha \dot{x} \left| \dot{x} \right| + \beta x + u$$

possède une dynamique linéaire par rapport aux variables $x(t)$ et $u(t)$, et non linéaire par rapport a $\dot{x}(t)$. Nous proposons d'utiliser une forme d'approximateur pour lequel le vecteur e des variables d'entrée est séparé en deux sous ensembles:

- le sous ensemble $x = [x_1, x_2, x_3, ..., x_n]$ des variables influençant linéairement (ou quasi linéairement) la sortie de la fonction f,
- le sous ensemble $z = [z_1, z_2, z_3, ..., z_p]$ des variables qui ont une influence fortement non linéaire sur la sortie de la fonction f, variables dites «variables de contexte».

Cette représentation alternative de f utilise une population d'approximations linéaires locales de cette fonction. Dans ce cadre, l'approximateur Ψ peut s'écrire

$$\hat{f}(x) = \Psi(z, x, W, W^0) = A(W, z) \cdot x + B(W^0, z) \tag{A.2}$$

où z est le vecteur à valeurs réelles de dimension p des **variables de contexte** du filtre Ψ et W et W^0 les paramètres du modèle. L'équation (A.2) exprime donc une dépendance des coefficients de l'application linéaire par rapport à des variables pertinentes que sont les variables de contexte. Les coefficients A et B de l'équation (A.2) sont respectivement un «tenseur» et un vecteur dont les termes $a_{i,j}$ et b_i sont

$$\forall i \in [1, m], \forall j \in [1, n], a_{i,j} = (w_{i,j})^T \cdot g(z) \text{ et } b_i = \left(w_i^0\right)^T \cdot g(z)$$

soit plus explicitement :

$$\begin{bmatrix} y_1 \\ \dots \\ \dots \\ \dots \\ y_m \end{bmatrix} = \Psi(z, x, W, W^0) = \begin{bmatrix} w_{1,1}^T \cdot g(z) & \dots & \dots & w_{1,n}^T \cdot g(z) \\ \dots & \dots & \dots & \dots \\ \dots & w_{i,j}^T \cdot g(z) & \dots & \dots \\ \dots. & \dots & \dots & \dots \\ w_{m,1}^T . g(z) & \dots & \dots & w_{m,n}^T . g(z) \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_n \end{bmatrix} + \begin{bmatrix} \left(w_1^0\right)^T \cdot g(z) \\ \dots \\ \dots \\ \dots \\ \left(w_m^0\right)^T \cdot g(z) \end{bmatrix}$$

Les paramètres du filtres sont donc rassemblés dans une population de $m(n+1)$ vecteurs de dimension k (le nombre total de paramètres est donc $km(n+1)$). Un changement de notation nous permet de proposer une autre écriture de la relation (A.2), plus proche de l'expression (A.1). On peut en effet écrire

$$\hat{f}(x) = \Psi(x, \varpi) = W'(x) \cdot g(z) \tag{A.3}$$

où encore

$$\begin{bmatrix} y_1 \\ \dots \\ \dots \\ \dots \\ y_m \end{bmatrix} = \begin{bmatrix} \varpi_{1,1}^T \cdot x + \varpi_{1,1}^0 & \dots & \dots & \varpi_{1,k}^T \cdot x + \varpi_{1,k}^0 \\ \dots & \dots & \dots & \dots \\ \dots & \varpi_{i,j}^T \cdot x + \varpi_{i,j}^0 & \dots & \dots \\ \dots & \dots & \dots & \dots \\ \varpi_{m,1}^T \cdot x + \varpi_{m,1}^0 & \dots & \dots & \varpi_{m,k}^T \cdot x + \varpi_{m,k}^0 \end{bmatrix} \cdot \begin{bmatrix} g_1(z) \\ g_2(z) \\ \dots \\ g_k(z) \end{bmatrix}$$

On voit apparaître explicitement dans les termes de la matrice W' les mk combinaisons linéaires à $(n+1)$ paramètres constituant **la population de fonctions linéaires** associée à Ψ. Chacune de ces fonction correspond à une approximation linéaire locale de la fonction $f(x)$ au point correspondant au centre de la fonction à base radiale associée à la fonction. Supposons par exemple que le vecteur de contexte z soit situé exactement au maximum $g_2^{max} = g_2(z)$ de la fonction à base radiale $g_2(z)$ et qu'en ce point les autres fonctions à bases radiales aient des valeurs négligeables devant $g_2(z)$. Alors l'estimateur $\hat{f}(x)$ sera localement (au point z) linéaire

puisque l'on peut écrire

$$\hat{f}(x) = \begin{bmatrix} y_1 \\ \dots \\ \dots \\ \dots \\ y_m \end{bmatrix} \simeq g_2^{\max} \begin{bmatrix} \varpi_{1,2}^T \cdot x + \varpi_{1,2}^0 \\ \dots \\ \varpi_{i,2}^T \cdot x + \varpi_{i,2}^0 \\ \dots \\ \varpi_{m,2}^T \cdot x + \varpi_{m,2}^0 \end{bmatrix}$$

Il reste à préciser les conditions dans lesquelles la méthode (A.3) est préférable à la version classique (A.1). Le premier cas se présente lorsque la fonction $f(x)$ est linéaire «paramétrisée» par z et du type $f(x) = h(z)^T x + h^0(z)$ ou h et h^0 sont des fonctions non linéaires. Dans ce cas, les termes $A(W, z)$ et $B(W^0, z)$ de (A.2) doivent donner respectivement une approximation de $h(z)$ et de $h^0(z)$. Mais la motivation plus générale est de proposer un développement de (A.1) à l'ordre 1. En effet, on peut d'une manière générale écrire (développement de taylor au premier ordre)

$$f(x) \simeq f(x_0) + \frac{\partial f}{\partial x}(x_0)^T \cdot (x - x_0) \simeq \left[f(x_0) - \frac{\partial f}{\partial x}(x_0)^T \cdot x_0 \right] + \frac{\partial f}{\partial x}(x_0)^T \cdot x \tag{A.4}$$

où x_0 est un point où $f(x_0)$ et $\frac{\partial f}{\partial x}(x_0)$ sont connus. La méthode (A.1) revient à obtenir une estimation de la valeur de $f(x)$ à partir de toutes les valeurs de la fonction $f(x)$ aux points x situés au centre des fonctions à base radiale (le terme $f(x_0)$ dans l'équation A.4, où x_0 correspond au centre d'une des fonctions à base radiale). La méthode (A.2) permet d'obtenir une approximation à partir de ces valeurs, mais utilise également des informations sur le gradient local de $f(x)$ (représentées par le terme $\frac{\partial f}{\partial x}(x_0)$ dans l'équation A.4).

Enfin, dans le cas particulier où $z = x$, la méthode (A.2) se rapproche d'un approximateur utilisant une gamme d'ondelettes. Supposons par exemple que les fonctions à base radiale impliquées soit des gaussiennes et que l'on se limite à l'approximation d'une fonction de $\Re^n$ dans $\Re$. On peut alors écrire

$$\hat{f}(x) = \sum_{i=1}^{i=n} \sum_{j=1}^{j=k} \left[w_{i,j} g_j(x) x_i + w_{i,j}^0 g_j(x) \right] \tag{A.5}$$

or si $g_j(x)$ est centrée sur x_j^0 et du type

$$g_j(x) = \exp(-\frac{(x - x_j^0)^T (x - x_j^0)}{\sigma^2})$$

alors

$$\frac{\partial g_j}{\partial x_i} = -\frac{2}{\sigma^2}(x_i - x_j^0) g_j(x) = \left(-\frac{2}{\sigma^2} \right) g_j(x) x_i + \left(\frac{2}{\sigma^2} x_j^0 \right) g_j(x)$$

Il est donc possible de réécrire l'équation (A.5) sous la forme

$$\hat{f}(x) = \sum_{i=1}^{i=n} \sum_{j=1}^{j=k} \left[\gamma_{i,j} \frac{\partial g_j}{\partial x_i}(x) + \gamma_{i,j}^0 g_j(x) \right]$$

où $\gamma_{i,j}$ et $\gamma_{i,j}^0$ représentent les coefficients associés respectivement à deux ondelettes ayant la forme d'une gaussienne et de sa dérivée.

Annexe B
Introduction au contrôle par surfaces glissantes

Dans cette annexe, nous proposons une introduction courte et simplifiée au contrôle par surfaces glissantes [230, Slotine et Li, 1991] . Le but de ce court chapitre est de montrer que la minimisation d'une variable intermédiaire (la variable "glissante") peut simplifier le contrôle d'un système d'ordre élevé (linéaire ou non) et peut conduire au développement de stratégies de contrôle très efficaces utilisant une combinaison de commandes en boucle ouverte et en boucle fermée. Considérons ainsi un système d'ordre n dont la dynamique est décrite par l'équation suivante

$$x^{(n)} = f(x^{(0)}, x^{(1)}, ..., x^{(n-1)}) + u(t)$$

où $x^{(i)}(t)$ est la dérivée d'ordre i de la sortie du système et $u(t)$ son entrée. La fonction f est supposée inconnue, mais on suppose également que l'on peut borner son écart à une estimation $\widehat{f}$ par une fonction positive F telle que

$$\forall t \geq 0, \left| f - \widehat{f} \right| < F$$

Si l'on définit l'erreur de poursuite instantanée $e(t) = x(t) - x_d(t)$ ($x_d(t)$ représentant la trajectoire désirée), alors on peut choisir, plutôt que de contrôler simultanément les dérivées successives de $x(t)$, de minimiser une seule variable scalaire $s(t)$ définie comme

$$s(t) = \sum_{i=1}^{i=n} a_i . e^{(i-1)}(t) \tag{B.1}$$

Les n coefficients a_i doivent être choisis tels que l'équation différentielle ci-dessus soit stable. L'erreur de poursuite $e(t)$ peut en effet être considérée comme la sortie d'un filtre linéaire dont le signal d'entrée est $s(t)$. Par conséquent, si un algorithme de contrôle parvient à une minimisation de $s(t)$, alors l'erreur de poursuite et ses dérivées successives seront également bornées.Pour cette minimisation, un critère simple et intuitif de minimisation est

$$V(t) = \frac{1}{2} s(t)^2$$

Cette fonction est positive par définition et sa dérivée temporelle est

$$\frac{\partial V}{\partial t} = s(t).\ \dot{s}\ (t)$$

D'après la théorie des fonctions de Lyapunov, si il est possible de construire un algorithme de contrôle assurant un signe négatif à $\frac{\partial V}{\partial t}$,$\forall t \geq 0$ alors $V(t)$ est une fonction de Lyapunov et $s(t)$ tend vers une limite finie.

D'après l'équation (B.1) ,

$$\dot{s}=\sum_{i=1}^{i=n} a_i.e^{(i)} = \sum_{i=1}^{i=n-1} a_i.e^{(i)} + a_n.e^{(n)} = \sum_{i=1}^{i=n-1} a_i.e^{(i)} + a_n.f + a_n.u - a_n.x^{(n)} \tag{B.2}$$

La meilleur approximation $\widehat{u}(t)$ d'une loi de contrôle telle que $\dot{s}= 0$ est

$$a_n.\widehat{u} = a_n.x_d^{(n)} - \sum_{i=1}^{i=n-1} a_i.e^{(i)} - a_n.\widehat{f}$$

Si cette loi de contrôle est introduite dans (B.2) alors,

$$\dot{s}= a_n.\left(f - \widehat{f}\right) \tag{B.3}$$

et $\dot{s}\ (t)$ dépend seulement des incertitudes concernant la fonction f décrivant la dynamique du système. De plus, si l'on ajoute un terme supplémentaire h(t) à la commande $\widehat{u}(t)$, l'équation (B.3) devient :

$$\dot{s}= a_n.\left(f - \widehat{f}\right) + a_n.h$$

Remarquons que ce dernier résultat montre que le système global comprenant le système original et le contrôleur générant la commande $\widehat{u}(t)$ se comporte comme un système du premier ordre en $s(t)$. Sa sortie s(t) peut ainsi être contrôlée en utilisant des stratégies de contrôle très simples comme par exemple "si l'erreur est négative, produire un signal suffisamment fort de signe contraire à celui du signal actuel (et vice versa). Cependant, cette loi de contrôle doit prendre en compte le fait que le terme $\left(f - \widehat{f}\right)$ est inconnu et seulement borné par une fonction connue F.

Ainsi, une stratégie très efficace consiste à introduire un terme discontinu à la commande continue $\widehat{u}(t)$ pour obtenir $\frac{\partial V}{\partial t} \leq 0, \forall t \geq 0$. Si k est une fonction de $\{x^{(0)}, x^{(1)}..., x^{(n-1)}\}$ et sgn la fonction signe, et si l'on écrit

$$u(t) = \widehat{u}(t) + h(t) = \widehat{u}(t) - k.sgn(s)$$

alors (B.3) devient

$$\dot{s} = a_n.\left(f - \widehat{f}\right) - k.a_n.sgn(s)$$

et

$$\frac{\partial V}{\partial t} = s(t).\ \dot{s}\ (t) = a_n.\left[s.\left(f - \widehat{f}\right) - k.\ |s|\right]$$

Posons ensuite $k = F + \eta$, avec a_n positif et η positif et suffisamment grand, alors

$$a_n.\left[s.\left(f - \widehat{f}\right) - k.\ |s|\right] \leq -a_n.\eta.\ |s| \leq 0$$

et, par conséquent, l'inégalité $\frac{\partial V}{\partial t} \leq 0, \forall t \geq 0$ est vérifiée et $s(t)$ tend vers 0.

Ce court développement montre finalement que l'on peut simplifier le contrôle d'un système linéaire ou non linéaire d'ordre élevé en minimisant non pas l'erreur de poursuite $e(t)$, mais une combinaison linéaire de $e(t)$ et de ses dérivées successives. Cette stratégie conduit à composer une commande comportant deux termes de natures différentes. le premier ($u(t)$) est une combinaison de termes fonctionnant en boucle ouverte et en boucle fermée dépendant à la fois du système et des paramètres de la variable glissante choisie. Le second terme ($h(t)$) est un signal de correction discontinu impliqué dans la stabilisation de la boucle de contrôle assurant ce rôle en raison des imprécisions affectant l'élaboration de $u(t)$. Dans cette étude expérimentale, nous suggérons que le mouvements rapides et intermittents produits par nos sujets jouent le même rôle stabilisateur que cette dernière composante de la commande.

Annexe C
La régression biplanaire

Une procédure de régression linéaire multiple permet d'établir une relation linéaire entre un ensemble de mesures scalaires y_i ($i \in [1, n]$) et un ensemble de vecteurs $\overline{x}_i = [x_{i,1}, x_{i,2}, ..., x_{i,k}]$ ($i \in [1, n]$) par la minimisation du critère dit des moindres carrés suivant

$$J = \frac{1}{n} \sum_{i=1}^{i=n} \left(y_i - \left[\sum_{j=1}^{j=k} a_j . x_{i,j} - b \right] \right)^2$$

Dans cette étude, nous cherchons les paramètres de deux plans parallèles approximant deux ensembles de points. Si $\left[y_i^{(1)}, \overline{x}_i^{(1)} \right]$ ($i \in \left[1, n^{(1)}\right]$) et $\left[y_r^{(2)}, \overline{x}_r^{(2)} \right]$ ($r \in \left[1, n^{(2)}\right]$) sont ces deux ensembles (correspondant ici à la mesure de l'erreur de poursuite et de ses dérivées au moment même du déclenchement des mouvements stéréotypés), le critère proposé dans cette régression dite "biplanaire" est

$$J = J^{(1)} + J^{(2)}$$

$$J = \frac{1}{n^{(1)}} \sum_{i=1}^{i=n^{(1)}} \left(y_i^{(1)} - (\sum_{j=1}^{j=k} a_j . x_{i,j}^{(1)} - b^{(1)}) \right)^2 + \frac{1}{n^{(2)}} \sum_{r=1}^{r=n^{(2)}} \left(y_r^{(2)} - (\sum_{j=1}^{j=k} a_j . x_{r,j}^{(2)} - b^{(2)}) \right)^2$$

L'ensemble des paramètres $\{a_1, a_2 ..., a_k, b_+, b_-\}$ minimisant J est la solution du système de $[k+2]$ d'équations linéaires suivant

$\left\{ \frac{\delta J}{\delta a_1} = 0, \frac{\delta J}{\delta a_2} = 0, ..., \frac{\delta J}{\delta a_k} = 0, \frac{\delta J}{\delta b^{(1)}} = 0, \frac{\delta J}{\delta b^{(2)}} = 0 \right\}$

et par exemple,

$$\forall m \in [1, k], \frac{\delta J}{\delta a_m} = -\frac{2}{n^{(1)}} \sum_{i=1}^{i=n^{(1)}} \Delta_i^{(1)} . x_{i,m}^{(1)} - \frac{2}{n^{(2)}} \sum_{i=1}^{i=n^{(2)}} \Delta_i^{(2)} . x_{i,m}^{(2)} = 0$$

avec

$$\Delta_i^{(1)} = y_i^{(1)} - \left[\sum_{j=1}^{j=k} a_j . x_{i,j}^{(1)} - b^{(1)} \right] \text{ et } \Delta_i^{(2)} = y_i^{(2)} - \left[\sum_{j=1}^{j=k} a_j . x_{i,j}^{(2)} - b^{(2)} \right]$$

Par analogie avec la procédure de régression linéaire multiple classique, il est possible de définir un coefficient de régression R obtenu par la relation

$$1 - R^2 = \left(J_{\min}^{(1)} + J_{\min}^{(2)}\right) / var(y)$$

où $J_{\min}^{(1)}$ et $J_{\min}^{(2)}$ sont les valeurs minimales des critères calculés avec l'ensemble des paramêtres $\left\{a_1, a_2, \ldots, a_k, b^{(1)}\right.$ obtenus par la résolution du système d'équations linéaires, et $var(y)$ est la variance globale de y calculée sur les deux ensembles de points ($n^{(1)} + n^{(2)}$ points).

Partie VI
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