行政院國家科學委員會專題研究計畫成果報告
利用 CMAC 類神經網路改善現存之飛彈縱向控制系統
Use CMAC neural network to improve existing missile longitudinal control system

一、中文摘要

　　本計畫將以兩種不同的方式把 CMAC 類神經網路應用於飛彈動態控制上：
1. 結合 CMAC 類神經網路與外迴圈(outer loop)以反置(inverse)包含內迴圈的飛彈動態系統。 這是貼近現代非線性控制的作法。
2. 結合 CMAC 類神經網路與 PD 控制器構成新型的外迴圈(outer loop)，以控制包含內迴圈的飛彈動態系統。 這是貼近古典控制的作法。

關鍵詞：飛彈；控制系統；類神經網路

Abstract

In this proposal, we will apply the CMAC neural networks to the missile control problem, in two different ways:
1. Combining the CMAC neural networks and the outer loop of the traditional missile autopilot to inverse the missile dynamics that contain the inner loop of the autopilot. This approach is more related to modern nonlinear control.
2. Integrating the CMAC neural networks and the original PID outer loop to form a new outer loop to control the missile dynamics that contain the inner loop of the autopilot.

Keywords: missile; CMAC neural networks; control systems

二、緣由與目的

　　不同於人工智慧，類神經網路是一種建構在數位運算的基礎上以模擬人腦的技術。但是現今可用的類神經網路模式仍然太過於簡單，以至於不能處理像我們大腦所能處理的控制問題。因此，他們大部分只用於學習非線性的映射。在類神經網路中處理控制問題較熱門的是 CMAC 類神經網路，因為 CMAC 有快速的學習能力，並且許多經驗都顯示 CMAC 在工業應用上有較佳的潛力。本計劃的主要目的在於針對我們新近的控制架構[17]設計控制器。經由**累加效應**與**遺忘效應**的相互配合，CMAC 控制器對於非常嚴重的非線性與不準確性可以快速反應，但是卻不會反應過度。

　　本計畫將以兩種不同的方式把 CMAC 類神經網路應用於飛彈動態控制上：
1. 結合 CMAC 類神經網路與外迴圈(outer loop)以反置(inverse)包含內迴圈的飛彈動態系統。 這是貼近現代非線性控制的作法。

主要的困難在於從尾翅角(tail-fin angle input)u 到垂直加速度(normal acceleration)N_z 的飛彈動態特性是非最小相位(non-minimum phase)的。基於攻角(angle of attack)Γ 與垂直加速度(normal acceleration)N_z 在動態上的密切關係，我們的規劃如下：
a. 將表現於垂直加速度(normal acceleration)N_z 的 reference command 經過適當的路逕規劃後轉換成表現於攻角(angle of attack)Γ 的

reference command。

b. 結合 CMAC 類神經網路與 PID 外迴圈 (outer loop)進行對於從尾翅角 (tail-fin angle input)u 到攻角 (angle of attack)r 的飛彈動態特性的反置(inverse)。

接下來我們介紹第二種方法。

2. 結合 CMAC 類神經網路與 PD 控制器構成新型的外迴圈(outer loop)，以控制包含內迴圈的飛彈動態系統。 這是貼近古典控制的作法。

此新型的外迴圈控制器是一個 CMAC 和一個 PD 控制器的平行組合，經過每次的取樣，由 CMAC 的輸出加上 PD 控制器的輸出而產生。 而在 CMAC 的學習上，則在每次取樣後，CMAC 會將 PD 控制器的輸出加到 CMAC 的 receptive field 上。這樣一個做法能產生積分效應以快速應付 nonlinearities 以及 uncertainties。同時這樣一個做法也能產生足夠的遺忘效應以免系統反應過度。

三、結果與討論

我們可據此得到一個飛彈動態特性的反置(inverse)如下

$$U = \left(\frac{QSd}{I_y} C_{Mu} - \frac{QS}{V_mW} C_{Nu} \cdot \sin r \cdot \dot{r} \right)^{-1}$$

$$\left\{ \ddot{r} - \frac{QSd}{I_y} \left[C_M(r) + C_{Mu} \cdot \left(K_r\dot{r} + K_rW_Ir \right) \right] - \right.$$

$$\left. \frac{QS}{V_mW} \begin{bmatrix} C_{Nr}(r)\cos r - C_N(r)\sin r - C_{Nu} \cdot \\ \left(K_r\dot{r} + K_rW_Ir \right)\sin r \end{bmatrix} \dot{r} \right\}$$

其中 $U = U_O + U_C$. 其 discrete time format 是
$$U(k) = f(r(k+1), r(k), r(k-1))$$
以利進行數位化控制。

整個 CMAC 類神經網路+傳統 PID 回授控制系統如圖八所示。在 CMAC 類神經網路之 recall process, CMAC 類神經網路之 Uc(k) 將和 CFC 外迴圈(i.e. Uₒ(k)) 合作以 track $r_{des}(k+1)$, 亦即
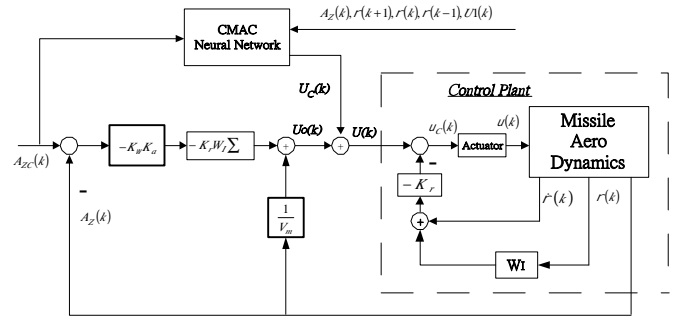$$U(k) = U_C(k) + U_o(k) = f(r_{des}(k+1), r(k), r(k-1))$$

Fig. 6 CMAC NN based autopilot

重整後, 可得
$$U_C(k) = f(r_{des}(k+1), r(k), r(k-1)) - K_rW_I \cdot A \cdot$$
$$(r_{des}(k+1) - r(k))/\Delta T - U1(k)$$
$$\equiv CMAC(r_{des}(k+1), r(k), r(k-1), U1(k))$$

當 $U(k)$ 被 applied 到系統後, the CMAC 類神經網路開始進行如下之學習
$$W_i(k+1) = W_i(k) +$$
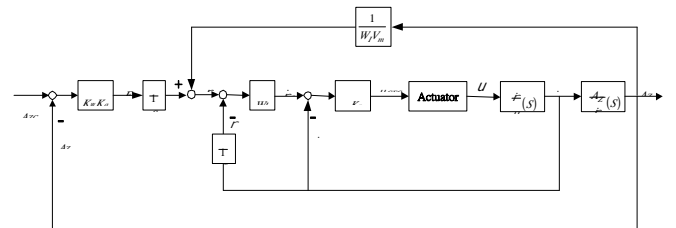$$\frac{\tilde{}}{g} \left[U(k) - U_o(k) - CMAC(r(k+1), r(k), r(k-1), U1(k)) \right]$$

Figure 7. AOA configuration of CFC pitch autopilot

電腦模擬:

由於 $\ddot{r} = Z_r\dot{r} + M_rr + M_uu + Z_u\dot{u}$, 尾翅的 maximum deflection and maximum deflection rate 被限制在 ±25 deg (0.436 rad) and 500 deg/s (8.72 rad/s)。 對 flight condition $M_u = -37.52 \ 1/s^2$ and $Z_u = -0.23 \ 1/s$ 而言，最大的 acceleration of AOA 將被限制為

$$\ddot{r}_{MAX} = |\ddot{r}|_{MAX} = 37.52 * 0.436 + 0.23 * 8.72 = 18.36 \left[\frac{rad}{s^2} \right]$$

假如我們進一步考慮 uncertainties of aerodynamic coefficients 以及 the restoring torque of missile body force，則在電腦模擬中，最大的 acceleration of AOA 將再被降到 $\ddot{r}_{MAX} = 10 \ rad/s^2$ 。
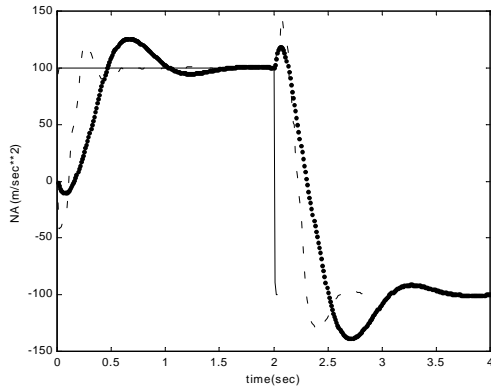
Figure 8 The performance of CMAC control system

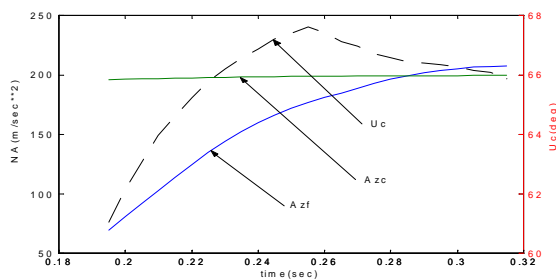Figure 9   The relationships between A_{ZC}, A_{zf} and U_C.

四、計畫成果自評

In this project we propose a way to integrate the CMAC with existing conventional flight controllers (CFC) to improve performance. Although we proposed a transformation on the CFC, no change in existing CFC design is needed. When the CMAC is disabled, the CMAC controller (which includes the CMAC and the CFC) reduces to the original CFC. The spirit of this research is in maintaining the CFC in its original form, so that existing CFC can be readily employed. And that, built upon the basic stability and performance provided by the CFC, the effect of the CMAC can be adjusted by tuning the learning rate $\tilde{~}$.

The locally learning property of the CMAC allows it to quickly approximate nonlinear mapping, and the *generalization* property can immediately convert the learned information into effective control. These are the reasons the CMAC controller can quickly improve the performance, particularly during the transient period. With its learning capability, the CMAC controller can also very well deal with uncertainties and parameter variations.

Even the CFC control system, which our CMAC control system is built upon, does not have a complete stability analysis. Nonetheless, the CFC prevails in traditional missile autopilot. In the future, more in testing and design can be done about the CMAC control system we proposed in this work.

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