

MAXIMUM TOLERANCE AND MAXIMUM GREATEST TOLERANCE

Weights and Threshold of Strict Separating Systems

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Keywords: Neural nets, Circuit-switching networks, Deterministic and structural pattern recognition.

Abstract: An important consideration when applying neural networks is the sensitivity to weights and threshold in strict separating systems representing a linearly separable function. Two parameters have been introduced to measure the relative errors in weights and threshold of strict separating systems: the tolerance and the greatest tolerance. Given an arbitrary separating system we study which is the equivalent separating system that provides maximum tolerance or/and maximum greatest tolerance.

1 INTRODUCTION

Recent research in Capacitive Threshold Logic (Sang-Hoon and Lee, 1995), (Ozdemir et al., 1996) and (Beiu et al., 2003) has revived interest in this area, and it has re-introduced some of the problems that have yet to be solved. One of the main issues of threshold logic is the application of neural networks to the problem of realizing Boolean functions, the linear separability problem has been dealt with, among others, in (Yao and Ostapko, 1968), (Roychowdhury et al., 1994), (Siu et al., 1995), (Picton, 1991), (Elizondo, 2004) and (Elizondo, 2006). Neural networks are usually designed to have the ability to learn and generalize.

A neural network is capable of setting and input-output mapping by adjusting its threshold and weights. How can network designers predict the effect of threshold and weight perturbations on neural networks' output, which are unavoidable because of limited precision of digital and analog hardware? What is then a tight bound for weights and threshold to prevent output deviation? Which is the sharpest bound one may consider for weights and threshold to maintain the linearly separable function unchange-

able? Is there any guideline for designing a more robust and safer neural network? These kind of problems were deeply studied in the sixties (Hu, 1960), (Elgot, 1961), (Myhill and Kautz, 1961) and (Winder, 1962), until (Hu, 1965) proposed as a solution to the main problem, a number (defined for each strict separating system) which he called, the *tolerance*. Recently (Freixas and Molinero, 2008a) proposed a new bound which improves the tolerance, the *greatest tolerance* (*G-tolerance*), and proved that the *G-tolerance* is the greatest bound one may consider.

In this work we consider two parameters for an arbitrary linearly separable switching function: the number of variables n and the number of types² of distinguished variables k . For each pair (n, k) we are interested in determining the maximum achievable value for the tolerance and for the *G-tolerance*. Moreover, we demonstrate that taking strict separating systems with positive integer (natural) weights are enough to our purpose.

2 PRELIMINARIES

Let Q be the set $\{0, 1\}$. For any given positive integer n , consider the cartesian power product $Q^n = Q \times \dots \times Q$. Thus, the elements of Q^n are the 2^n ordered n -tuples (x_1, \dots, x_n) , with variables $x_i \in \{0, 1\}$ for all $i = 1, \dots, n$. By a *switching function* of n variables, we mean a function $f : Q^n \rightarrow Q$ from the n -

²A type is a set of variables which are equivalent among them.

*Research partially supported by Grants SGR 2009-1029 and ALBCOM-SGR 2009-1137 of "Generalitat de Catalunya", programme TIN2006-11345 (ALINEX) from the Spanish "Ministerio de Educación y Ciencia", MTM2009-08037 from the Spanish Science and Innovation Ministry, and 9-INCREC-11 of "(PRE/756/2008) Ajuts a la iniciació/reincorporació a la recerca (Universitat Politècnica de Catalunya)"

cube Q^n into Q . If f is not surjective then either $\{x \in Q^n : f(x) = 0\} = \emptyset$ or $\{x \in Q^n : f(x) = 1\} = \emptyset$ that is, f is a constant function. The two constant functions are called the two *trivial* switching functions. A switching function is *monotonic* if: (i) f is not decreasing in each argument; and (ii) $f(\bar{0}) = 0$ and $f(\bar{1}) = 1$. The two constant Boolean functions are usually considered to be monotonic, but here the restriction (ii) relegates them to be non-monotonic. In a monotonic switching function a variable i is *relevant* if there exists at least $x, y \in Q^n$, $x \geq y$ with $f(x) = 1$, $f(y) = 0$, $x_i \neq y_i$ and $y_j = x_j$ for $j \neq i$. Note that *irrelevant* (that is, not relevant) variables do not add any value to the outcome f , i.e., if i is irrelevant then $f(x) = f(y)$ whenever $x_i \neq y_i$ and $y_j = x_j$ for $j \neq i$.

A switching function $f : Q^n \rightarrow Q$ is a *linearly separable function* or *threshold function* if it admits a system of $n + 1$ real numbers T, w_1, \dots, w_n , denoted by $[T; w_1, \dots, w_n]$ such that for each arbitrary point $x = (x_1, \dots, x_n)$ in the n -cube Q^n we have

$$\begin{aligned} w(x) &\geq T, & \text{if } f(x) = 1, \\ w(x) &< T, & \text{if } f(x) = 0; \end{aligned}$$

being $w(x) = \sum_{i=1}^n w_i x_i$.

The n real numbers w_1, \dots, w_n in this system are called the *weights*, and the first real number T is referred to as the *threshold*. By the finiteness of Q^n it is always possible to modify the threshold in such a way that the previous definition could be rewritten using strict inequalities. In this case, the system is called a *strict separating system* for the linear separable function f . Thus, from now on we will just consider strict separating systems.

Note that a switching function has only two possible values, true or false. True or false can also be referred, as we do here, to as 1 or 0 often used in computer programming, on or off as seen with computer hardware circuits, firing or resting used to describe the state of an artificial neuron, functioning state or failing state as seen with reliability, and voting in favor (“yea”) or against (“nay”) in binary decision-making mechanisms. If one draws the graph of a linearly separable switching function of two variables in a square with the elements of Q^2 as vertices, it takes only one straight line to separate the true outputs from the false outputs. In general, for n variables it is required an $(n - 1)$ -hyperplane to separate the true outputs from the false outputs.

It is important to point out that both, the tolerance and the G -tolerance, we are going to introduce next, are defined for each strict separating system and, thus they depend on the threshold and the set of weights chosen to implement the linearly separable switching function.

2.1 The Tolerance

In this part we are going to define the tolerance introduced by (Hu, 1960). Let A denote the maximum of the function $w(x)$ for all x such that $f(x) = 0$, $A = \max_{x: f(x)=0} w(x)$, and let B denote the minimum of the function $w(x)$ for all x such that $f(x) = 1$, $B = \min_{x: f(x)=1} w(x)$.

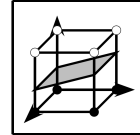


Figure 1: Separating hyperplane for a threshold function defined in Q^3 .

The two trivial switching functions are linearly separable; if $f \equiv 0$, we set $A = -\infty$; if $f \equiv 1$, we set $B = \infty$. Then we have $A < T < B$. Let m denote the smallest of the two positive numbers $T - A$ and $B - T$. On the other hand, let $M = |T| + \sum_{i=1}^n |w_i|$. Then, for each point $x \in Q^n$ we have $|T| + \sum_{i=1}^n |w_i| x_i \leq M$. Let $\lambda_1, \dots, \lambda_n$ and Λ be $n + 1$ arbitrary real numbers and let $w'_i = (1 + \lambda_i) w_i$ for all $i = 1, \dots, n$, and $T' = (1 + \Lambda) T$. Then, the real numbers $\lambda_1, \dots, \lambda_n$ and Λ represent the relative errors if we use the numbers w'_1, \dots, w'_n and T' instead of the original non-null numbers w_1, \dots, w_n and T as weights and threshold. In other words, if we initially start with $[T; w_1, \dots, w_n]$ which is transformed into $[T'; w'_1, \dots, w'_n]$ then $\lambda_i = \frac{w'_i - w_i}{w_i}$ for all $i = 1, \dots, n$ and $\Lambda = \frac{T' - T}{T}$ where it is required w_i and T to be different from zero. That is to say, these numbers are the *relative errors* in weights and threshold, that is why we use the term “error” in the title of this paper.

Theorem 2.1 (Hu, 1965) *Let $f : Q^n \rightarrow Q$ be an arbitrary linearly separable switching function of n variables, let $[T; w_1, \dots, w_n]$ be a given strict separating system³ for f and let $\tau[T; w_1, \dots, w_n] := \frac{m}{M}$ be the tolerance for $[T; w_1, \dots, w_n]$. If $|\lambda_i| < \tau$ for each $i = 1, \dots, n$ and if $|\Lambda| < \tau$ then $[T'; w'_1, \dots, w'_n]$ is a strict separating system for the given linearly separable switching function f .*

Hu called this positive number the *tolerance* of the separating system and denoted it $\tau[T; w_1, \dots, w_n]$.

Note that the tolerance is well-defined, in fact, as $w(\bar{0}) = 0$ for any strict separating system, it occurs that $T \neq 0$ and so $M \neq 0$.

³ $\tau[T; w_1, \dots, w_n]$ is denoted by τ if there is no confusion about the strict linearly separating system

2.2 The Greatest Tolerance

(Freixas and Molinero, 2008a) improves the *Hu's tolerance*. They find the greatest positive real number δ such that if $|\Lambda| < \delta$ and $|\lambda_i| < \delta$, for all $i = 1, \dots, n$; then $[T'; w'_1, \dots, w'_n]$ is equivalent to $[T; w_1, \dots, w_n]$, i.e., both strict separating systems still represent the same linearly separable switching function.

Definition 2.2 (Freixas and Molinero, 2008a) Given a strict separating system $[T; w_1, \dots, w_n]$, for each $x \in Q^n$ let $a(x) = |w(x) - T|$, $b(x) = |T| + \sum_{i=1}^n |w_i| x_i$ and $\chi[T; w_1, \dots, w_n] = \min_{x \in Q^n} \frac{a(x)}{b(x)}$. This number⁴ is called the greatest tolerance (briefly, *G-tolerance*) of $[T; w_1, \dots, w_n]$. Note that the *G-tolerance* of the strict separating system $[T; w_1, \dots, w_n]$ depends on the chosen threshold and weights. Because of the finiteness of Q^n , χ is attained for, at least one $x \in Q^n$, let $x^0 \in Q^n$ be one of the points attaining the *G-tolerance*.

Theorem 2.3 (Freixas and Molinero, 2008a) Let $f: Q^n \rightarrow Q$ be an arbitrarily linearly separable switching function of n variables and let $[T; w_1, \dots, w_n]$ be a given strict separating system for f . If $|\lambda_i| < \chi$ for each $i = 1, \dots, n$ and if $|\Lambda| < \chi$ then:

- (i) $[T'; w'_1, \dots, w'_n]$ is a strict separating system for the given linearly separable switching function f .
- (ii) χ is the greatest upper bound for the constants $\lambda_1, \dots, \lambda_n, \Lambda$.

3 MAXIMUM TOLERANCE AND MAXIMUM G-TOLERANCE

Let f be an arbitrary monotonic⁵ linearly separable switching function of n variables, now we are looking for a strict linearly⁶ separating system $[T; w_1, \dots, w_n]$ representing f with *maximum achievable tolerance* and *maximum achievable G-tolerance*.

We start by relating the tolerance (the *G-tolerance*) of an arbitrary strict separating system with the tolerance (*G-tolerance*) of a strict separating system with natural weights.

Theorem 3.1 If $[T; w_1, \dots, w_n] \in \mathbb{R} \times \mathbb{R}^n$ is a real strict separating system, then there exists an equivalent strict separating natural system, i.e., a system with natural weights w'_1, \dots, w'_n , with the same tolerance and the same *G-tolerance*.

⁴ $\chi[T; w_1, \dots, w_n]$ is denoted by χ if there is no confusion about the strict separating system

⁵From now on we will omit the word *monotonic*.

⁶From now on we will omit the word *linearly*.

Note that, even though the weights are the same natural numbers for both systems (the system applied to the tolerance and the system applied to the *G-tolerance*), the threshold can be a different real number for each system.

An obvious corollary for maximums arises:

Corollary 3.2 If $[T; w_1, \dots, w_n] \in \mathbb{R} \times \mathbb{R}^n$ is a real strict separating system with maximum tolerance (maximum *G-tolerance*), then there exists an equivalent strict separating natural system with the same maximum tolerance (maximum *G-tolerance*).

Second, we propose a way to get maximum tolerance and maximum *G-tolerance*.

Theorem 3.3 Maximum tolerance and maximum *G-tolerance* among all equivalent strict separating systems are attained when the weights are natural numbers and their sum is the minimum achievable one.

Given a strict separating system with fixed weights, $[T; w_1, \dots, w_n]$, it is known (Freixas and Molinero, 2008a) that adjusting the corresponding threshold, $\frac{A+B}{2}$ for the tolerance and \sqrt{AB} for the *G-tolerance*, the system achieves the maximum tolerance and the maximum *G-tolerance*, respectively. Thus, given a strict separating system of an arbitrary separable switching function, we have a procedure to compute a strict separating system with maximum tolerance or/and maximum *G-tolerance*, respectively.

For instance, let $[5; 8, 8, 6, 3, 3]$ be a strict separating system, then $\tau = \frac{1}{5+28} = 0.0303\dots$; but the equivalent strict separating natural system with natural weights having minimum sum and threshold equal to $\frac{A+B}{2}$, i.e., $[\frac{3}{2}; 2, 2, 2, 1, 1]$, achieves the maximum available tolerance $\tau' = \frac{1/2}{3/2+8} = 0.0526\dots$. In the same vein, the strict separating system $[5; 8, 8, 6, 3, 3]$ has $\chi = \frac{1}{11} = 0.0909\dots$, but the equivalent strict separating natural system with natural weights having minimum sum and threshold equal to \sqrt{AB} , i.e., $[\sqrt{2}; 2, 2, 2, 1, 1]$, achieves the maximum available *G-tolerance* $\chi' = \frac{\sqrt{2}-1}{\sqrt{2}+1} = 0.1715\dots$

Another important new result is how we get the maximum tolerance with n variables:

Proposition 3.4 The maximum tolerance for n variables is given by the following strict separating (natural) system: $[\frac{1}{2}; 1, \dots, 1]$, and such tolerance is $\tau = 1/(1+2n)$.

Any other strict (natural or not) separating system (of non null weights) with tolerance τ' fulfills $\tau' \leq \tau$.

Finally, we extend this result for systems with n variables and k distinguished types of variables, i.e., with exactly k non-equivalent variables:

Conjecture 3.5 The maximum achievable tolerance for n variables and k types of distinguished variables

is obtained by the following strict separable system:

$$[k-1/2; k, k-1, k-2, \dots, 1, \underbrace{1, \dots, 1}_{n-k}]$$

and such a tolerance is $\tau = 1/(2n + k^2 + k - 1)$.

Again, any other strict linearly (natural or not) separating system (of non null weights) with tolerance τ' fulfills $\tau' \leq \tau$.

In the same vein, we establish the corresponding conjecture for the G -tolerance:

Conjecture 3.6 *The maximum G -tolerance for n variables and k types ($k > 1$) of distinguished variables is given by the following strict separable system:*

$$[\sqrt{k(k-1)}; k, k-1, k-2, \dots, 1, \underbrace{1, \dots, 1}_{n-k}].$$

and such a G -tolerance is $\chi = \frac{\sqrt{k(k-1)} - (k-1)}{\sqrt{k(k-1)} + (k-1)}$.

In general, given a strict separating system for an arbitrary separable switching function, we are able to find an equivalent strict separating system (with natural weights having minimum integer sum) achieving the maximum tolerance and the maximum G -tolerance. Moreover, it is known, see (Freixas and Molinero, 2008b), that for less than 8 variables all linearly separable switching functions have, up to isomorphism, a unique strict separating system with natural weights having minimum sum. So, we only need to adjust the threshold, $\frac{A+B}{2}$ for the tolerance and \sqrt{AB} for the G -tolerance, for these systems to achieve the maximum tolerance and the maximum G -tolerance, respectively. Note that for 8 variables the situation changes: There are 154 linearly separable switching functions, up to isomorphism, with two strict separating systems having natural weights and minimum sum.

4 FUTURE WORK

Generating a huge number of random strict separating natural systems and then to conjecturate what distribution follows the tolerance, the maximum tolerance, the G -tolerance and the maximum G -tolerance.

It is also interesting to provide tables of all, up to isomorphism, linearly separable switching functions of a reasonable high number of variables with: a strict separating system achieving its tolerance; its tolerance; a strict separating system achieving its G -tolerance; and its G -tolerance.

Although the computational limitation (complexity) of finding the tolerance and the G -tolerance of a

given strict separating system (both are NP-hard), it will be of interest to develop an efficient algorithm able to calculate the tolerance and the greatest tolerance for strict separating systems with a reasonable high number of variables.

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