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Pooling designs with surprisingly high degree of error correction in a finite vector space

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ABSTRACT

Pooling designs are standard experimental tools in many biotechnical applications. It is well-known that all famous pooling designs are constructed from mathematical structures by the “containment matrix” method. In particular, Macula's designs (resp. Ngo and Du's designs) are constructed by means of the containment relation of subsets (resp. subspaces) in a finite set (resp. vector space). In [J. Guo, K. Wang, A construction of pooling designs with high degree of error correction, J. Combin. Theory Ser. A 118 (2011) 2056–2058], we generalized Macula's designs and obtained a family of pooling designs with higher degree of error correction. In this paper we consider, as a generalization of Ngo and Du's designs, q -analogue of the above designs, and obtain a family of pooling designs with surprisingly high degree of error correction. Our designs and Ngo and Du's designs have the same numbers of items and pools, but the error-tolerance property of our design is much better than that of Ngo and Du's designs when the dimension of the space is large enough.

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1. Introduction

A group test is applicable to an arbitrary subset of clones with two possible outcomes: a negative outcome indicates that all clones in the subset are negative, and a positive outcome indicates otherwise. A pooling design is a specification of all tests such that they can be performed simultaneously, with the goal being to identify all positive clones with a small number of tests [1–3,7]. A pooling design is usually represented by a binary matrix with columns indexed with items and rows indexed with pools. A cell (i, j) contains a 1-entry if and only if the i th pool contains the j th item. By treating a column as a set of row indices intersecting the column with a 1-entry, we can talk about the union of several columns. A binary matrix is s^e -disjunct if every column has at least $e + 1$ 1-entries not contained in the union of any other s columns [9]. An s^0 -disjunct matrix is also called s -disjunct. An s^e -disjunct matrix is called *fully s^e -disjunct* if it is not $s_1^{e_1}$ -disjunct whenever $s_1 > s$ or $e_1 > e$. An s^e -disjunct matrix is $\lfloor e/2 \rfloor$ -error-correcting [4].

For positive integers $k \leq n$, let $[n] = \{1, 2, \dots, n\}$ and $\binom{[n]}{k}$ denote the collection of all k -subsets of $[n]$.

Macula [8,9] proposed a novel way of constructing disjunct matrices by means of the containment relation of subsets in $[n]$.

Definition 1.1 ([8]). For positive integers $1 \leq d < k < n$, let $M(d, k, n)$ be the binary matrix with rows indexed with $\binom{[n]}{d}$ and columns indexed with $\binom{[n]}{k}$ such that $M(A, B) = 1$ if and only if $A \subseteq B$.

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D'yachkov et al. [5] discussed the error-correcting property of $M(d, k, n)$.

Theorem 1.1 ([5]). For positive integers $1 \leq d < k < n$ and $1 \leq s \leq d$, $M(d, k, n)$ is fully s^{e_1} -disjunct, where $e_1 = \binom{k-s}{d-s} - 1$.

In [6], we generalized Macula's construction and obtained a family of pooling designs with higher degree of error correction.

Definition 1.2 ([6]). For positive integers $1 \leq d < k < n$ and $0 \leq i \leq d$, let $M(i; d, k, n)$ be the binary matrix with rows indexed with $\binom{[n]}{d}$ and columns indexed with $\binom{[n]}{k}$ such that $M(A, B) = 1$ if and only if $|A \cap B| = i$.

Theorem 1.2 ([6]). Let $1 \leq s \leq i$, $\lfloor (d+1)/2 \rfloor \leq i \leq d < k$ and $n - k - s(k + d - 2i) \geq d - i$. Then:

- (i) $M(i; d, k, n)$ is an s^{e_2} -disjunct matrix, where $e_2 = \binom{k-s}{i-s} \binom{n-k-s(k+d-2i)}{d-i} - 1$;
- (ii) for a given k , if $i < d$, then $\lim_{n \rightarrow \infty} \frac{e_2+1}{e_1+1} = \infty$.

Let \mathbb{F}_q be a finite field with q elements, where q is a prime power. For a positive integer n , let \mathbb{F}_q^n be an n -dimensional vector space over \mathbb{F}_q . For positive integers $k \leq n$, let $\left[\begin{smallmatrix} [n] \\ k \end{smallmatrix} \right]_q$ be the set of all k -dimensional subspaces of \mathbb{F}_q^n . A matrix representation of a subspace P is a matrix whose rows form a basis for P . When there is no danger of confusion, we use the same symbol to denote a subspace and its matrix representation.

Let m_1 and m_2 be two integers. For brevity we use the *Gaussian coefficient*

$$\left[\begin{smallmatrix} m_2 \\ m_1 \end{smallmatrix} \right]_q = \frac{\prod_{t=m_2-m_1+1}^{m_2} (q^t - 1)}{\prod_{t=1}^{m_1} (q^t - 1)}.$$

For convenience, we set $\left[\begin{smallmatrix} m_2 \\ 0 \end{smallmatrix} \right]_q = 1$ and $\left[\begin{smallmatrix} m_2 \\ m_1 \end{smallmatrix} \right]_q = 0$ whenever $m_1 < 0$ or $m_2 < m_1$. Then, by Wan [13],

$$\left| \left[\begin{smallmatrix} [n] \\ k \end{smallmatrix} \right]_q \right| = \left[\begin{smallmatrix} n \\ k \end{smallmatrix} \right]_q.$$

As a q -analogue of Macula's designs, Ngo and Du [12] constructed a family of disjunct matrices by using the containment relation of subspaces in \mathbb{F}_q^n .

Definition 1.3 ([12]). For positive integers $1 \leq d < k < n$, let $M_q(d, k, n)$ be the binary matrix with rows indexed with $\left[\begin{smallmatrix} [n] \\ d \end{smallmatrix} \right]_q$ and columns indexed with $\left[\begin{smallmatrix} [n] \\ k \end{smallmatrix} \right]_q$ such that $M_q(A, B) = 1$ if and only if $A \subseteq B$.

D'yachkov et al. [4] discussed the error-tolerance property of $M_q(d, k, n)$.

Theorem 1.3 ([4]). For positive integers $1 \leq d < k < n$, $k - d \geq 2$ and $1 \leq \bar{s} \leq q(q^{k-1} - 1)/(q^{k-d} - 1)$, $M_q(d, k, n)$ is $\bar{s}^{\bar{e}_1}$ -disjunct, where $\bar{e}_1 = q^{k-d} \left[\begin{smallmatrix} k-1 \\ d-1 \end{smallmatrix} \right]_q - (\bar{s} - 1)q^{k-d-1} \left[\begin{smallmatrix} k-2 \\ d-1 \end{smallmatrix} \right]_q - 1$. In particular, if $\bar{s} \leq q + 1$, then $M_q(d, k, n)$ is fully $\bar{s}^{\bar{e}_1}$ -disjunct.

Nan and Guo [10] generalized Ngo and Du's construction and obtained a family of pooling designs.

Definition 1.4 ([10]). For positive integers $1 \leq d < k < n$ and $\max\{0, d + k - n\} \leq i \leq d$, let $M_q(i; d, k, n)$ be the binary matrix with rows indexed with $\left[\begin{smallmatrix} [n] \\ d \end{smallmatrix} \right]_q$ and columns indexed with $\left[\begin{smallmatrix} [n] \\ k \end{smallmatrix} \right]_q$ such that $M_q(A, B) = 1$ if and only if $\dim(A \cap B) = i$.

Note that $M_q(i; d, k, n)$ and $M_q(d, k, n)$ have the same size. In [10], the error-tolerance property of $M_q(i; d, k, n)$ is not well expressed. In this paper, we discuss again the error-tolerance property of $M_q(i; d, k, n)$.

2. The main results

In this section, we discuss the error-tolerance property of $M_q(i; d, k, n)$. We begin with a useful lemma.

Lemma 2.1. Suppose $\max\{0, r + m - n\} \leq j \leq r$ and $j \leq m \leq n$. Let P be an m -dimensional subspace of \mathbb{F}_q^n and let W be a j -dimensional subspace of P . Then the number of r -dimensional subspaces of \mathbb{F}_q^n intersecting P at W is $f(j, r, n; m) = q^{(r-j)(m-j)} \left[\begin{smallmatrix} n-m \\ r-j \end{smallmatrix} \right]_q$. Moreover the function $f(j, r, n; m + \alpha)$ about α is decreasing for $0 \leq \alpha \leq n + j - m - r$.

Proof. Since the general linear group $GL_n(\mathbb{F}_q)$ acts transitively on the set of such pairs (P, W) , we may assume that $P = (I^{(m)} \ 0^{(m, n-m)})$, $W = (I^{(j)} \ 0^{(j, n-j)})$. Let Q be any r -dimensional subspace of \mathbb{F}_q^n satisfying $P \cap Q = W$. Then Q has a matrix representation of the form

$$\begin{pmatrix} I^{(j)} & 0^{(j, m-j)} & 0^{(j, n-m)} \\ 0^{(r-j, j)} & A_2 & A_3 \end{pmatrix},$$

where A_2 is an $(r-j) \times (m-j)$ matrix and A_3 is an $(r-j)$ -dimensional subspace of \mathbb{F}_q^{n-m} . Therefore, $f(j, r, n; m) = q^{(r-j)(m-j)} \begin{bmatrix} n-m \\ r-j \end{bmatrix}_q$.

Since

$$\begin{aligned} f(j, r, n; m) - f(j, r, n; m+1) &= q^{(r-j)(m-j)} \begin{bmatrix} n-m \\ r-j \end{bmatrix}_q - q^{(r-j)(m+1-j)} \begin{bmatrix} n-m-1 \\ r-j \end{bmatrix}_q \\ &= (q^{r-j} - 1) \frac{q^{(r-j)(m-j)} \prod_{l=n-m-(r-j)+1}^{n-m-1} (q^l - 1)}{\prod_{l=1}^{r-j} (q^l - 1)} \\ &\geq 0, \end{aligned}$$

the desired result follows. \square

Theorem 2.2. Let i, d, k, n be positive integers with $\lfloor (d+1)/2 \rfloor \leq i \leq d < k$ and $n-k-\bar{s}(k+d-2i) \geq d-i$. If $k-i \geq 2$ and $1 \leq \bar{s} \leq q(q^{k-1}-1)/(q^{k-i}-1)$, then the following hold:

(i) $M_q(i; d, k, n)$ is an \bar{s}^2 -disjunct matrix, where

$$\bar{e}_2 = q^{(d-i)(k+\bar{s}(k+d-2i)-i)} \begin{bmatrix} n-k-\bar{s}(k+d-2i) \\ d-i \end{bmatrix}_q \left(q^{k-i} \begin{bmatrix} k-1 \\ i-1 \end{bmatrix}_q - (\bar{s}-1)q^{k-i-1} \begin{bmatrix} k-2 \\ i-1 \end{bmatrix}_q \right) - 1;$$

(ii) for a given k , if $i < d$, then $\lim_{n \rightarrow \infty} \frac{\bar{e}_2+1}{\bar{e}_1+1} = \infty$.

Proof. (i) Let $B_0, B_1, \dots, B_{\bar{s}} \in \begin{bmatrix} [n] \\ k \end{bmatrix}_q$ be any $\bar{s}+1$ distinct columns of $M_q(i; d, k, n)$. Note that B_0 contains $\begin{bmatrix} k \\ i \end{bmatrix}_q$ many i -dimensional subspaces. To obtain the minimum number of i -dimensional subspaces of B_0 not contained in B_j for each $1 \leq j \leq \bar{s}$, we may assume that $\dim(B_0 \cap B_j) = k-1$ and $\dim(B_0 \cap B_j \cap B_l) = k-2$ for any two distinct $j, l \in \{1, 2, \dots, \bar{s}\}$. Then B_1 contains $\begin{bmatrix} k-1 \\ i \end{bmatrix}_q$ many i -dimensional subspaces of B_0 , while each of $B_2, B_3, \dots, B_{\bar{s}}$ contains at most $\begin{bmatrix} k-1 \\ i \end{bmatrix}_q - \begin{bmatrix} k-2 \\ i \end{bmatrix}_q$ many i -dimensional subspaces of B_0 not contained in B_1 . Consequently, the number of i -dimensional subspaces of B_0 not contained in $B_1, B_2, \dots, B_{\bar{s}}$ is at least

$$\begin{aligned} \alpha &= \begin{bmatrix} k \\ i \end{bmatrix}_q - \begin{bmatrix} k-1 \\ i \end{bmatrix}_q - (\bar{s}-1) \left(\begin{bmatrix} k-1 \\ i \end{bmatrix}_q - \begin{bmatrix} k-2 \\ i \end{bmatrix}_q \right) \\ &= q^{k-i} \begin{bmatrix} k-1 \\ i-1 \end{bmatrix}_q - (\bar{s}-1)q^{k-i-1} \begin{bmatrix} k-2 \\ i-1 \end{bmatrix}_q. \end{aligned}$$

Let $D \in \begin{bmatrix} [n] \\ d \end{bmatrix}_q$ with $\dim(D \cap B_0) = i$. If there exists $j \in \{1, 2, \dots, \bar{s}\}$ such that $\dim(D \cap B_j) = i$, by $(D \cap B_0) + (D \cap B_j) \subseteq D$, we have

$$\begin{aligned} \dim(B_0 \cap B_j) &\geq \dim(D \cap B_0 \cap B_j) \\ &= \dim(D \cap B_0) + \dim(D \cap B_j) - \dim((D \cap B_0) + (D \cap B_j)) \\ &\geq 2i - d. \end{aligned}$$

Suppose $\dim(B_0 \cap B_j) \geq 2i - d$ for each $j \in \{1, 2, \dots, \bar{s}\}$. Then

$$\begin{aligned} \dim(B_0 + B_1 + \dots + B_{\bar{s}}) &= \dim(B_0 + B_1 + \dots + B_{\bar{s}-1}) + \dim B_{\bar{s}} - \dim((B_0 + B_1 + \dots + B_{\bar{s}-1}) \cap B_{\bar{s}}) \\ &\leq \dim(B_0 + B_1 + \dots + B_{\bar{s}-1}) + \dim B_{\bar{s}} - \dim(B_0 \cap B_{\bar{s}}) \\ &\leq \dim(B_0 + B_1 + \dots + B_{\bar{s}-1}) + k + d - 2i \\ &\leq \dim B_0 + \bar{s}(k + d - 2i) \\ &= k + \bar{s}(k + d - 2i). \end{aligned}$$

Table 1
Disjunct property of $M_2(d, 8, 60)$ and $M_2(i; d, 8, 60)$.

(i, d)	\bar{s}	\bar{e}_1	\bar{e}_2	Remarks
(1, 2)	2	6111	36893488146882232319	Theorem 2.2
(1, 3)	2	74927	3544607988605033156167647492927651839	Theorem 2.3
(2, 3)	4	54095	599519146661432524799	Theorem 2.2
(1, 4)	2	177815	284599986330728289752034695103377217756856319	Theorem 2.3
(2, 4)	4	155495	28799857511436549196854689617936383999	Theorem 2.2
(3, 4)	8	110855	800925501358079	Theorem 2.2

Let P be a given i -dimensional subspace of B_0 not contained in $B_1, B_2, \dots, B_{\bar{s}}$. By Lemma 2.1, the number of d -dimensional subspaces D in \mathbb{F}_q^n satisfying $D \cap (B_0 + B_1 + \dots + B_{\bar{s}}) = P$ is at least

$$q^{(d-i)(k+\bar{s}(k+d-2i)-i)} \begin{bmatrix} n-k-\bar{s}(k+d-2i) \\ d-i \end{bmatrix}_q.$$

Observe that $D \cap B_0 = P$ and $\dim(D \cap B_j) \neq i$ for each $j \in \{1, 2, \dots, \bar{s}\}$. Therefore, the number of d -dimensional subspaces D in \mathbb{F}_q^n satisfying $\dim(D \cap B_0) = i$ and $\dim(D \cap B_j) \neq i$ for each $j \in \{1, 2, \dots, \bar{s}\}$ is at least

$$\alpha q^{(d-i)(k+\bar{s}(k+d-2i)-i)} \begin{bmatrix} n-k-\bar{s}(k+d-2i) \\ d-i \end{bmatrix}_q.$$

Since $\bar{e}_2 \geq 0$, we have $\alpha > 0$, which implies that

$$\bar{s} \leq \frac{q^{k-i} \begin{bmatrix} k-1 \\ i-1 \end{bmatrix}_q}{q^{k-i-1} \begin{bmatrix} k-2 \\ i-1 \end{bmatrix}_q} = \frac{q(q^{k-1}-1)}{q^{k-i}-1}.$$

Hence, (i) holds.

(ii) is straightforward by (i) and Theorem 1.3. \square

Theorem 2.3. Let i, d, k, n be positive integers with $1 \leq i < \lfloor (d+1)/2 \rfloor$ and $d < k, n - (\bar{s}+1)k \geq d-i$. If $1 \leq \bar{s} \leq q(q^{k-1}-1)/(q^{k-i}-1)$, then the following hold:

(i) $M_q(i; d, k, n)$ is an $\bar{s}\bar{e}_2$ -disjunct matrix, where

$$\bar{e}_2 = q^{(d-i)((\bar{s}+1)k-i)} \begin{bmatrix} n-(\bar{s}+1)k \\ d-i \end{bmatrix}_q \left(q^{k-i} \begin{bmatrix} k-1 \\ i-1 \end{bmatrix}_q - (\bar{s}-1)q^{k-i-1} \begin{bmatrix} k-2 \\ i-1 \end{bmatrix}_q \right) - 1;$$

(ii) for a given k , $\lim_{n \rightarrow \infty} \frac{\bar{e}_2+1}{\bar{e}_1+1} = \infty$.

Proof. The proof is similar to that of Theorem 2.2, and will be omitted. \square

For $q = 2, k = 8, n = 60$, Table 1 shows the disjunct property of our designs and Ngo and Du's designs for small i, d, \bar{s} .

3. Concluding remarks

- (i) For given positive integers $d < k$, $\lim_{n \rightarrow \infty} \frac{\begin{bmatrix} n \\ d \end{bmatrix}_q}{\begin{bmatrix} n \\ k \end{bmatrix}_q} = 0$. This shows that the test-to-item ratio of $M_q(i; d, k, n)$ is small enough when n is large enough. By Theorems 2.2 and 2.3, our pooling designs are much better than Ngo and Du's designs when n is large enough.
- (ii) Ngo [11] improved the error-tolerance property of $M_q(d, k, n)$ for $\bar{s} \geq q+2, \bar{s} \geq q+3$ and $\bar{s} \geq q+4$, respectively. By a similar method, we also can improve the error-tolerance property of $M_q(i; d, k, n)$ for these cases.
- (iii) For positive integers $1 \leq d < k < n$, it seems to be interesting to consider the error-tolerance property of $M_q(0; d, k, n)$.

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