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On Reliability Approach to Multiple Hypotheses Testing and Identification of Probability Distributions of Two Stochastically Coupled Objects

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Abstract

This paper is devoted to logarithmically asymptotically optimal hypotheses testing and identification for a model consisting of two stochastically related objects. It is supposed that L_1 possible probability distributions are known for the first object and the second object is distributed according to one of $L_1 \times L_2$ given conditional distributions depending on the distribution index and the current observed state of the first object. The matrix of interdependencies of all possible pairs of the error probability exponents in asymptotically optimal tests of distributions of both objects is studied. The identification of the distributions of two objects gives an answer to the question whether r_1-th and r_2-th distributions occurred, or not on the first and the second objects, correspondingly.

1. Introduction

As a development of the results on multiple hypotheses testing concerning probability distributions of one object [1] in paper [2] Ahlswede and Haroutunian and in [3] Haroutunian formulated a number of problems on multiple hypotheses testing and identification for one and multiple objects. Haroutunian and Hakobyan considered in [4] the problem of many hypotheses testing and in [5] the problem of the indentification of distributions for two independent objects. Solutions of analogical problems concerning Markov distributions are obtained in works of Haroutunian and Grigoryan [9], Haroutunian and Navaei [11]. In [7], [8] and [10] Haroutunian and Yessayan solved the problem of many hypotheses testing for two objects under different kinds of dependence. We study characteristics of procedures of logarithmically asymptotically optimal testing and identification of probability distributions of two stochastically dependent objects.

Let X_1 and X_2 be random variables (RVs) taking values in the same finite set $\mathcal{X}$ and $\mathcal{P}(\mathcal{X})$ be the space of all possible distributions on $\mathcal{X}$. If X_1 and X_2 take values in different sets $\mathcal{X}_1$ and $\mathcal{X}_2$ only the notations became more complicated, so we omit this "generalization". There are given L_1 probability distributions (PDs) $G_{l_1} = \{G_{l_1}(x^1),\ x^1 \in \mathcal{X}\}$, $l_1 = \overline{1, L_1}$, from $\mathcal{P}(\mathcal{X})$. The first object is characterized by RV X_1 which has one of these L_1 PDs and the second object is dependent on the first and is characterized by RV X_2 which can have one of $L_1 \times L_2$ conditional PDs $G_{l_2/l_1} = \{G_{l_2/l_1}(x^2|x^1),\ x^1, x^2 \in \mathcal{X}\}$, $l_1 = \overline{1, L_1}$, $l_2 = \overline{1, L_2}$. Let $(\mathbf{x}_1, \mathbf{x}_2) = ((x_1^1, x_1^2), (x_2^1, x_2^2), ...(x_N^1, x_N^2))$ be a sequence of results of N independent observations of pair of objects. Joint PDs $G_{l_1,l_2}(x^1, x^2)$, $l_1 = \overline{1, L_1}$, $l_2 = \overline{1, L_2}$, where $G_{l_1,l_2}(x^1, x^2) = G_{l_1}(x^1)G_{l_2/l_1}(x^2|x^1)$. The probability $G^N_{l_1,l_2}(\mathbf{x}_1, \mathbf{x}_2)$ of vector $(\mathbf{x}_1, \mathbf{x}_2)$ is the following product:

$$G^N_{l_1,l_2}(\mathbf{x}_1, \mathbf{x}_2) = G^N_{l_1}(\mathbf{x}_1)G^N_{l_2/l_1}(\mathbf{x}_2|\mathbf{x}_1) = \prod_{n=1}^{N} G_{l_1}(x_n^1)G_{l_2/l_1}(x_n^2|x_n^1).$$

with $G^N_{l_1}(\mathbf{x}_1) = \prod_{n=1}^{N} G_{l_1}(x_n^1)$ and $G^N_{l_2/l_1}(\mathbf{x}_2|\mathbf{x}_1) = \prod_{n=1}^{N} G_{l_2/l_1}(x_n^2|x_n^1)$.

For the object characterized by X_1 the non-randomized test $\varphi_1^N(\mathbf{x}_1)$ can be determined by partition of the sample space $\mathcal{X}^N$ on L_1 disjoint subsets $\mathcal{A}^N_{l_1} = \{\mathbf{x}_1 : \varphi_1^N(\mathbf{x}_1) = l_1\}$, $l_1 = \overline{1, L_1}$, i.e. the set $\mathcal{A}^N_{l_1}$ consists of vectors $\mathbf{x}_1$ for which the PD G_{l_1} is adopted. The probability $\alpha^N_{l_1|m_1}(\varphi_1^N)$ of the erroneous acceptance of PD G_{l_1} provided that G_{m_1} is true, $l_1, m_1 = \overline{1.L_1}$, $m_1 \neq l_1$, is defined by the set $\mathcal{A}^N_{l_1}$

$$\alpha^N_{l_1|m_1}(\varphi_1^N) \triangleq G^N_{m_1}(\mathcal{A}^N_{l_1}).$$

We define the probability to reject G_{m_1}, when it is true, as follows

$$\alpha^N_{m_1|m_1}(\varphi_1^N) \triangleq \sum_{l_1 \neq m_1} \alpha^N_{l_1|m_1}(\varphi_1^N) = G^N_{m_1}(\overline{\mathcal{A}^N_{m_1}}). \tag{2}$$

Denote by φ_1, φ_2 and Φ the infinite sequences of tests. Corresponding error probability exponents $E_{l_1|m_1}(\varphi_1)$ for test φ_1 are defined as

$$E_{l_1|m_1}(\varphi_1) \triangleq \overline{\lim_{N\to\infty}} -\frac{1}{N}\log \alpha^N_{l_1|m_1}(\varphi_1^N),\ \ m_1 . l_1 = \overline{1.L_1}. \tag{3}$$

For brevity we call them reliabilities. It follows from (2) and (3) that

$$E_{m_1|m_1}(\varphi_1) = \min_{l_1 \neq m_1} E_{l_1|m_1}(\varphi_1),\ \ l_1, m_1 = \overline{1.L_1},\ l_1 \neq m_1. \tag{4}$$

We shall reformulate now the Theorem from [1] for the case of one object with L_1 hypotheses. This requires some notions and notations. For some PD $Q = \{Q(x^1), x^1 \in \mathcal{X}\}$ the entropy $H_Q(X_1)$ and the informational divergence $D(Q||G_{l_1})$, $l_1 = \overline{1.L_1}$, are defined as follows:

$$H_Q(X_1) \triangleq -\sum_{x^1 \in \mathcal{X}} Q(x^1)\log Q(x^1),$$

$$D(Q||G_{l_1}) \triangleq \sum_{x^1 \in \mathcal{X}} Q(x^1)\log\frac{Q(x^1)}{G_{l_1}(x^1)}.$$

For given positive numbers $E_{1|1}, ..., E_{L-1|L-1}$, let us consider the following sets of PDs $Q = \{Q(x^1), x^1 \in \mathcal{X}\}$:

$$\mathcal{R}_{l_1} \triangleq \{Q:\ D(Q||G_{l_1}) \leq E_{l_1|l_1}\},\ \ l_1 = \overline{1, L_1 - 1}, \tag{5a}$$

$$\mathcal{R}_{L_1} \triangleq \{Q:\ D(Q||G_{l_1}) > E_{l_1|l_1},\ \ l_1 = \overline{1, L_1 - 1}\}, \tag{5b}$$

and the elements of the reliability matrix $\mathbf{E}^*$ of the LAO test:

$$E^*_{l_1|l_1} = E^*_{l_1|l_1}(E_{l_1|l_1}) \triangleq E_{l_1|l_1},\ l_1 = \overline{1, L_1 - 1}, \tag{6a}$$

$$E^*_{l_1|m_1} = E^*_{l_1|m_1}(E_{l_1|l_1}) \triangleq \inf_{Q \in \mathcal{R}_{l_1}} D(Q||G_{m_1}),\ m_1 = \overline{1, L_1},\ m_1 \neq l_1,\ l_1 = \overline{1, L_1 - 1}, \tag{6b}$$

$$E^*_{L_1|m_1} = E^*_{L_1|m_1}(E_{1|1}, E_{2|2}, \dots, E_{L_1-1|L_1-1}) \triangleq \inf_{Q \in \mathcal{R}_{L_1}} D(Q||G_{m_1}),\ m_1 = \overline{1, L_1 - 1}, \tag{6c}$$

$$E^*_{L_1|L_1} = E^*_{L_1|L_1}(E_{1|1}, E_{2|2}, \dots, E_{L_1-1|L_1-1}) \triangleq \min_{l_1 = \overline{1, L_1 - 1}} E^*_{l_1|L_1}. \tag{6d}$$

Theorem 1[1]: *If all distributions G_{l_1}, $l_1 = \overline{1, L_1}$, are different in the sense that $D(G_{l_1}||G_{m_1}) > 0$, $l_1 \neq m_1$, and the positive numbers $E_{1|1}, E_{2|2}, \dots, E_{L-1|L-1}$ are such that the following inequalities hold*

$$E_{1|1} < \min_{l_1 = \overline{2, L_1}} D(G_{l_1}||G_1),$$
$$\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \tag{7}$$
$$E_{m_1|m_1} < \min\Big(\min_{l_1 = \overline{m_1 + 1, L_1}} D(G_{l_1}||G_{m_1}),\ \min_{l_1 = \overline{1, m_1 - 1}} E^*_{l_1|m_1}(E_{l_1|l_1})\Big),\ m_1 = \overline{2, L_1 - 1},$$

then there exists a LAO sequence of tests φ_1^*, the reliability matrix of which $\mathbf{E}^* = \{E_{l_1|m_1}(\varphi_1^*)\}$ is defined in (6) and all elements of it are positive.

Inequalities (7) are necessary for existence of tests sequence with reliability matrix $\mathbf{E}$ having in diagonal given elements $E^*_{l_1|l_1}$, $l_1 = \overline{1, L_1 - 1}$, and all other elements positive .

Corollary 1: *If in contradiction to conditions (7) one, or several diagonal element $E_{l_1|l_1}$, $l_1 \in [1, L_1 - 1]$, of the reliability matrix are equal to zero, then the elements of the matrix determined in functions of this $E_{l_1|l_1}$ will be given as in the case of Stain's lemma [11], [12]*

$$E'_{l_1|m_1}(E_{l_1|l_1}) = D(G_{l_1}||G_{m_1}),\quad m_1 = \overline{1, L_1},\ m_1 \neq l_1,$$

and the remaining elements of the matrix $\mathbf{E}(\varphi^*)$ are defined by $E_{l_1|l_1} > 0$, $l_1 \neq m_1$, $l_1 = \overline{1, L_1 - 1}$, as follows from Theorem 1:

$$E'_{l_1|m_1} = \inf_{Q: D(Q||G_{l_1}) \leq E_{l_1|l_1}} D(Q||G_{m_1}),$$

$$E'_{L_1|m_1} = \inf_{Q: D(Q||G_i) > E_{l_1|l_1},\ i = \overline{1, L_1 - 1}} D(Q||G_{m_1}).$$

2. Identification of the Probability Distribution of One Object

First it is necessary to formulate the concept of LAO approach to the identification problem for one object, which was introduced in [2] and [3], see also [10]. We have one object, and there are known $L_1 \geq 2$ possible PDs. Identification is the answer to the question: whether r_1-th distribution is correct, or not. As in the testing problem, the answer must be given on the base of a sample $\mathbf{x}$ with the help of an appropriate test.

There are two error probabilities for each $r_1 \in [1, L_1]$: the probability $\alpha_{l_1 \neq r_1|m_1 = r_1}(\varphi_N)$ to accept l-th PD different from r_1, when PD r_1 is in reality, and the probability $\alpha_{l_1 = r_1|m_1 \neq r_1}(\varphi_N)$ that r_1 is accepted, when it is not correct.

The probability $\alpha_{l_1\neq r_1|m_1=r_1}(\varphi_N)$ coincides with the probability $\alpha_{r_1|r_1}(\varphi_N)$ which is equal to $\sum\limits_{l_1:l_1\neq r_1}\alpha_{l_1|r_1}(\varphi_N)$. The corresponding reliability $E_{l_1\neq r_1|m_1=r_1}(\varphi)$ is equal to $E_{r_1|r_1}(\varphi)$ which satisfies the equality (4).

Reliability approach to identification means to determine the optimal dependence of $E^*_{l_1=r_1|m_1\neq r_1}$ upon given $E^*_{l_1\neq r_1|m_1=r_1}=E^*_{r_1|r_1}$, which can be an assigned value satisfying conditions (7). Solution of this problems uses knowledge of some a priori PD of the hypotheses.

The result from paper [2] is valid for the first object.

Theorem 2: *In the case of distinct PDs $G_1, G_2, \ldots, G_{L_1}$, under condition that the probabilities of all L_1 hypotheses are positive the reliability of $E_{l_1=r_1|m_1\neq r_1}$ for given $E_{l_1\neq r_1|m_1=r_1}=E_{r_1|r_1}$ is the following:*

$$E_{l_1=r_1|m_1\neq r_1}(E_{r_1|r_1})=\min_{m_1:m_1\neq r_1}\inf_{Q:D(Q\|G_{r_1})\leq E_{r_1|r_1}}D(Q\|G_{m_1}),\;\; r_1\in[1,L_1].$$

3. LAO Testing and Identification of the Probability Distributions for Two Stochastically Coupled Objects.

The test, which we denote by Φ^N, is a procedure of making decision about unknown indices of PDs on the base of results of N observations $(\mathbf{x}_1,\mathbf{x}_2)$. For the objects characterized by X_1, X_2 the non-randomized test $\Phi^N(\mathbf{x}_1,\mathbf{x}_2)$ can be determined by partition of the sample space $(\mathcal{X}\times\mathcal{X})^N$ on $L_1\times L_2$ disjoint subsets $\mathcal{A}^N_{l_1,l_2}=\{\mathbf{x}_1,\mathbf{x}_2:\ \Phi^N(\mathbf{x}_1,\mathbf{x}_2)=l_1,l_2\}$, $l_1=\overline{1,L_1}$, $l_2=\overline{1,L_2}$ i.e. the set $\mathcal{A}^N_{l_1,l_2}$ consists of vectors $\mathbf{x}_1,\mathbf{x}_2$ for which the PD G_{l_1,l_2} is adopted. The probability $\alpha^N_{l_1,l_2|m_1,m_2}(\Phi^N)$ of the erroneous acceptance of PD G_{l_1,l_2} provided that G_{m_1,m_2} is true, $l_1,m_1=\overline{1,L_1}, l_2,m_2=\overline{1,L_2}$ $(m_1,m_2\neq(l_1,l_2)$ is defined by the set $\mathcal{A}^N_{l_1,l_2}$

$$\alpha^N_{l_1,l_2|m_1,m_2}(\Phi^N)\triangleq G^N_{m_1,m_2}(\mathcal{A}^N_{l_1,l_2}). \tag{8}$$

We define the probability to reject G_{m_1,m_2}, when it is true, as follows

$$\alpha^N_{m_1,m_2|m_1,m_2}(\Phi^N)\triangleq\sum_{(l_1,l_2)\neq(m_1,m_2)}\alpha^N_{l_1,l_2|m_1,m_2}(\Phi^N)=G^N_{m_1,m_2}(\overline{\mathcal{A}^N_{m_1,m_2}}). \tag{9}$$

We study the reliabilities of the sequence of tests Φ

$$E_{l_1,l_2|m_1,m_2}(\Phi)\triangleq\overline{\lim_{N\to\infty}}-\frac{1}{N}\log\alpha^N_{l_1,l_2|m_1,m_2}(\Phi^N),\ l_1,m_1=\overline{1,L_1},\ l_2,m_2=\overline{1,L_2}. \tag{10}$$

From (9) and (10) we have

$$E_{m_1,m_2|m_1,m_2}(\Phi)=\min_{(l_1,l_2)\neq(m_1,m_2)}E_{l_1,l_2|m_1,m_2}(\Phi),\ l_1,m_1=\overline{1,L_1},\ l_2,m_2=\overline{1,L_2}. \tag{11}$$

We call the matrix $\mathbf{E}(\Phi)=\{E_{l_1,l_2|m_1,m_2}(\Phi),\ l_1,m_1=\overline{1,L_1},\ l_2,m_2=\overline{1,L_2}\}$ the reliability matrix of the sequence of tests Φ. Our aim is to investigate the reliability matrix of optimal tests, and the conditions ensuring positivity of all its elements.

We use some notions and estimates from [12], [13]. For given positive numbers $E_{1,1|1,1},\ldots,E_{L_1,L_2-1|L_1,L_2-1}$, let us consider the following sets of PDs $QoV\triangleq\{Q(x^1)V(x^2|x^1), x^1,x^2\in\mathcal{X}\}$:

$$\mathcal{R}_{l_1,l_2} \triangleq \{QoV: \ D(QoV||G_{l_1,l_2}) \leq E_{l_1,l_2|l_1,l_2}\}, \ l_1=\overline{1,L_1}, l_2=\overline{1,L_2-1} \quad (12a)$$

$$\mathcal{R}_{L_1,L_2} \triangleq \{QoV: \ D(QoV||G_{l_1,l_2}) > E_{l_1,l_2|l_1,l_2}, \ l_1=\overline{1,L_1}, l_2=\overline{1,L_2-1}\}, \quad (12b)$$

and the elements of the reliability matrix $\mathbf{E}^*$ of the LAO test:

$$E^*_{l_1,l_2|l_1,l_2} = E^*_{l_1,l_2|l_1,l_2}(E_{l_1,l_2|l_1,l_2}) \triangleq E_{l_1,l_2|l_1,l_2}, \ l_1=\overline{1,L_1}, l_2=\overline{1,L_2-1} \quad (13a)$$

$$E^*_{l_1,l_2|m_1,m_2} = E^*_{l_1,l_2|m_1,m_2}(E_{l_1,l_2|l_1,l_2}) \triangleq \inf_{QoV\in\mathcal{R}_{l_1,l_2}} D(QoV||G_{m_1,m_2}), \ m_1=\overline{1,L_1}, \ m_2=\overline{1,L_2}$$
$$(l_1,l_2)\neq(m_1,m_2), \ l_1=\overline{1,L_1}, l_2=\overline{1,L_2-1} \quad (13b)$$

$$E^*_{L_1,L_2|m_1,m_2} = E^*_{L_1,L_2|m_1,m_2}(E_{1,1|1,1}, E_{1,2|1,2}, E_{1,3|1,3}\ldots, E_{L_1,L_2-1|L_1,L_2-1}) \triangleq$$
$$\inf_{QoV\in\mathcal{R}_{L_1,L_2}} D(QoV||G_{m_1,m_2}), \ m_1=\overline{1,L_1}, m_2=\overline{1,L_2-1} \quad (13c)$$

$$E^*_{L_1,L_2|L_1,L_2} = E^*_{L_1,L_2|L_1,L_2}(E_{1,1|1,1}, E_{1,2|1,2}, E_{1,3|1,3}\ldots, E_{L_1,L_2-1|L_1,L_2-1}) \triangleq$$
$$\min_{l_1=\overline{1,L_1}} \min_{l_2=\overline{1,L_2-1}} E^*_{l_1,l_2|L_1,L_2}. \quad (13d)$$

For simplicity we can take $(X_1,X_2)=Y$, $\mathcal{X}\times\mathcal{X}=\mathcal{Y}$ and $\mathbf{y}=(y_1,y_2,\ldots,y_N)\in\mathcal{Y}^N$, where $y_n=(x^1_n,x^2_n)$, $n=\overline{1,N}$, then we will have $L_1\times L_2=L$ new hypotheses for one object $G_{1,1}(\mathbf{x}_1,\mathbf{x}_2)=F_1(\mathbf{y})$, $G_{1,2}(\mathbf{x}_1,\mathbf{x}_2)=F_2(\mathbf{y})$, $G_{1,3}(\mathbf{x}_1,\mathbf{x}_2)=F_3(\mathbf{y})$,....$G_{1,L_2}(\mathbf{x}_1,\mathbf{x}_2)=F_{L_2}(\mathbf{y})$, $G_{2,1}(\mathbf{x}_1,\mathbf{x}_2)=F_{L_1+1}(\mathbf{y})$,....,$G_{l_1,l_2}(\mathbf{x}_1,\mathbf{x}_2)=F_{(l_1-1)L_1+l_2}(\mathbf{y})$, $l_1=\overline{1,L_1}$, $l_2=\overline{1,L_2}$,. $\alpha_{l_1,l_2|m_1,m_2}=\alpha'_{l|m}$, $l_1=\overline{1,L_1}$, $l_2=\overline{1,L_2}$, $E_{l_1,l_2|m_1,m_2}=E'_{l|m}$, $l_1=\overline{1,L_1}$, $l_2=\overline{1,L_2}$ and thus we have brought the original problem to the case of one object with L hypotheses. Now we can reformulate Theorem 1 and Theorem 2 for these notations:

Theorem 3[1]: *If all distributions F_l, $l=\overline{1,L}$, are different in the sense that $D(F_l||F_m)>0$, $l\neq m$, and the positive numbers $E'_{1|1}, E'_{2|2},\ldots,E'_{L-1|L-1}$ are such that the following inequalities hold*

$$\begin{array}{c} E'_{1|1} < \min\limits_{l=\overline{2,L}} D(F_l||F_1), \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ E'_{m|m} < \min(\min\limits_{l=\overline{m+1,L}} D(F_l||F_m), \ \min\limits_{l=\overline{1,m-1}} E^{*'}_{l|m}(E'_{l|l})), \ m_1=\overline{2,L}, \end{array} \quad (14)$$

then there exists a LAO sequence of tests Φ^*, the reliability matrix of which $\mathbf{E}^{*'}=\{E'_{l|m}(\Phi^*)\}$ is defined in (13) and all elements of it are positive.

Inequalities (14) are necessary for existence of tests sequence with reliability matrix $\mathbf{E}'$ having in diagonal given elements $E^{*'}_{l|l_1}$, $l=\overline{1,L-1}$, and all other elements positive.

Theorem 4: *In the case of distinct PDs $F_1,F_2,\ldots,F_L$, under condition that the probabilities of all L hypotheses are positive the reliability of $E'_{l=r|m\neq r}$ for given $E'_{l\neq r|m=r}=E'_{r|r}$ is the following:*

$$E'_{l=r|m\neq r}(E'_{r|r}) = \min_{m:m\neq r} \inf_{QoV:D(QoV\|F_r)\leq E'_{r|r}} D(QoV\|F_m), \ \ r\in[1,L].$$

Remark 1: The problems of hypotheses testing and identification for more than two stochastically dependent objects can be solved analogously, only the notations for error probabilities and corresponding reliabilities will be combrous.

Remark 2: If we try to consider the test Φ^N as composed by a pair of tests φ^N_1 and φ^N_2 for the separate objects: $\Phi^N=(\varphi^N_1,\varphi^N_2)$, we will see that for N large enough the error probabilities of second object don't approach 0, so it is impossible to solve these problems with the methods similar to applied in [8] and [10] .

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Ստոխաստիկորեն կախյալ օբյեկտների հավանականային բաշխումների նկատմամբ վարկածների ստուգման և նույնականացման հուսալիության մոտեցման մասին

Ե. Ա. Հարությունյան և Ա. Օ. Եսայան

Ամփոփում

Դիտարկված են ստոխաստիկորեն կախյալ երկու օբյեկտների նկատմամբ վարկածների ստուգման և նույնականացման խնդիրները: Առաջին օբյեկտը կարող է բաշխված լինել տրված հավանականային բաշխումներից մեկով, իսկ երկրորդը՝ կախված առաջինից, տրված պայմանական հավանականային բաշխումներից մեկով: Ուսումնասիրվել է վարկածների օպտիմալ տեստավորման դեպքում երկու օբյեկտների նկատմամբ սխալների հավանականությունների ցուցիչների (հուսալիությունների) փոխկախվածությունը և ստացվել է երկու ստոխաստիկորեն կախյալ օբյեկտների հավանականային բաշխումների ասիմպտոտորեն օպտիմալ նույնականացման խնդրի լուծումը: