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BOUNDARY FIELD PROBLEMS AND COMPUTER SIMULATION
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NUMERICALLY STABLE SYMBOLICAL COMBINATORY MODEL OF POLYNOMIAL APPROXIMATION FOR PROBLEMS OF IDENTIFICATION AND IMITATION MODELLING

SKAITLISKI STABILS SIMBOLISKS KOMBINATORISKAIS POLINOMIĀLĀS APROKSIMĀCIJAS MODELIS IDENTIFIKĀCIJAS UN IMITĀCIJAS MODELĒŠANAS PROBLĒMĀM

Genadijs Burov, Dr.sc.ing., researcher
Riga Technical University, Faculty of Computer Science and Information Technology
Environment Modelling Centre
Address: 1/4 Meza Street, LV-1048, Riga, Latvia
Phone: +371 67089511
E-mail: emc@cs.rtu.lv

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Introduction

In the problems of computer control and diagnosis of analog technical objects, it is necessary to find their mathematical models from the experimental measurements of their output signals. For this purpose, there is a necessary amount of the aprioristic information about the object, gathered during the design and industrial manufacturing stages of the object. It is represented in the object's technical documentation, in particular, in the form of its transfer function. Admissions are specified on its parameters, and that allows creating a set of operators, suitable for imitation modelling of various operational conditions of the object. On their basis, a set of the bases of reference models, in which the spectral factors of Fourier transform, can be determined from the experimental realizations of output signals. Such factors can give the information, suitable for diagnosing the condition of the object.

With this purpose, various methods of approximation are applied. In particular, as such bases can lead to solving degenerate systems of equations, orthogonal polynomials are used for the formation of the bases. As them, in particular, orthogonal Laguerre, Legendre, Chebyshev and other polynomials are used.

It facilitates the inversion of the matrices of equation systems, but their application leads to results with abstract contents. They do not reflect the physical properties of the identified object and their practical use is complicated.

Therefore, there is a problem of using non-orthogonal bases that would have the best physical interpretation. For solving this problem, it is offered to apply non-conventional methods for the inversion of the matrices of equation systems generated on the basis of polynomial functions of any kind. Inverse matrices are offered to find in the analytical form, not applying the traditional numerical algorithms. This problem cannot be solved by the traditional methods. It is offered to be solved on the basis of symbolical analytical methods with the application of symbolical combinatory models (SC models) [1, 2, 3, 8, 9, 10].

The developed new forms of algorithms should be suitable for their application in computers working in the modes of parallel calculations. Therefore, they should have a parallel architecture that could be coordinated with the parallel architecture of the computer.

Symbolical combinatory model for finding Gramian matrix

The spectrum of the Fourier transform is found as a solution of the system of N conditional equations

$$F \cdot \overline{\alpha} = \overline{y}. \tag{1}$$

This is a system of conditional equations, and the number of equations is bigger than the number of variables. It is folded with the application of the method of the least squares (MLS) into a system of normal equations with a square Gramian matrix

$$\{F \cdot \overline{\alpha} = \overline{y}\} \Rightarrow \{(F^T \cdot F) \cdot \overline{\alpha} = F^T \cdot \overline{y}\}; \quad \overline{\alpha} = G^{-1} \cdot \overline{u}; \tag{2}$$

$$G^{-1} = \left(F^T \cdot F\right)^{-1}; \overline{u} = F^T \cdot \overline{y}. \tag{3}$$

It is necessary to find the expression of the vector $\overline{\alpha}$ of factors of Fourier spectrum. In this case, the experimentally measured signal *y(t)* can be expressed as a linear combination of the functions of a known kind

$$y(x) = \alpha_1 f_1(x) + \alpha_2 f_2(x) + \cdots + \alpha_n f_n(x). \tag{4}$$

The vector $\overline{u}$ (3) represents a projection of experimentally measured signal on the sub-space of the polynomial functions. It demands the numerical calculation of the values of polynomial functions on a grid of the argument values of. The problem of finding the inverse matrix $G^{-1} = \left(F^T \cdot F\right)^{-1}$ in the analytical form is put forward.
The problem of approximation will be reduced to the representation of the output signal of the object of an unknown analytical form by a linear combination of the functions of a known kind. As such, the polynomial functions are considered

$$\begin{aligned} &f_1(x) = a_{10} + a_{11}x + a_{12}x^2 + \cdots + a_{1n}x^n; \\ &f_2(x) = a_{20} + a_{21}x + a_{22}x^2 + \cdots + a_{2n}x^n; \\ &\ldots\ldots \\ &f_m(x) = a_{n0} + a_{m1}x + a_{m2}x^2 + \cdots + a_{m\,n}x^n. \end{aligned} \tag{5}$$

From them, the Fourier basis is made

$$F^{[N \times n]} = \begin{bmatrix} f_1(\Delta x) & f_2(\Delta x) & \cdots & f_m(\Delta x) \\ f_1(2\Delta x) & f_2(2\Delta x) & \cdots & f_m(2\Delta x) \\ \cdots & \cdots & \cdots & \cdots \\ f_1(N\Delta x) & f_2(N\Delta x) & \cdots & f_m(N\Delta x) \end{bmatrix}; N \rangle n. \tag{6}$$

We use a uniform step of function quantization. The set of the argument values can be represented by an interval of the natural series $\overline{x}^{(N)} = [(1.\overline{N}) \cdot \Delta x]$

$$f_1(x_r) = a_{10} + a_{11}(r \cdot \Delta x) + a_{12}(r \cdot \Delta x)^2 + \cdots + a_{1n}(r \cdot \Delta x)^n;$$
$$f_2(x_r) = a_{20} + a_{21}(r \cdot \Delta x) + a_{22}(r \cdot \Delta x)^2 + \cdots + a_{2n}(r \cdot x)^n;$$
$$\ldots\ldots$$
$$f_L(x_r) = a_{L0} + a_{L1}(r \cdot \Delta x) + a_{L2}(r \cdot \Delta x)^2 + \cdots + a_{L\,n}(r \cdot \Delta x)^n. \tag{7}$$

The matrix $F^{[N\times m]}$ in view of the expressions (2) we shall present as

$$F \Rightarrow U^{(N\times n)} \cdot A^{(n\times m)}; \tag{8}$$

$$U^{(N\times n)} = \begin{Vmatrix} x_1^{\ 0} & x_1^{\ 1} & x_1^{\ 2} & \cdots & x_1^{\ n-1} \\ x_2^{\ 0} & x_2^{\ 1} & x_2^{\ 2} & \cdots & x_2^{\ n-1} \\ x_3^{\ 0} & x_3^{\ 1} & x_3^{\ 2} & \cdots & x_3^{\ n-1} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ x_N^{\ 0} & x_N^{\ 1} & x_N^{\ 2} & \cdots & x_N^{\ n-1} \end{Vmatrix}; \quad A^{(N\times n)} \begin{bmatrix} a_{10} & a_{20} & \cdots & a_{m0} \\ a_{11} & a_{21} & \cdots & a_{m1} \\ a_{12} & a_{22} & \cdots & a_{m2} \\ \cdots & \cdots & \cdots & \cdots \\ a_{1n-1} & a_{2n-1} & \cdots & a_{m\,n-1} \end{bmatrix}. \tag{9}$$

Let’s introduce these designations in (2) and (3) as

$$G = F^T \cdot F \Rightarrow A^T \cdot M \cdot A; \quad Z^{(n\times n)} = U^T \cdot U. \tag{10}$$

$$\overline{\alpha} = H \cdot \overline{u}; \quad H = \left\lfloor \left(A^T\right)^{-1} \cdot M \cdot A^{-1} \right\rfloor; \quad M = Z^{-1}; \quad \overline{u} = F^T \cdot \overline{y}. \tag{11}$$

Let’s define the SC model for the formation of the matrix H.

Formation of Gramian matrix of system of Fourier decomposition

We use the ordered numerical sequences from [1, 6, 7]. They will be used as coordinate systems for allocation of sub-matrixes and argument sets of operators. Such sequences are formed on the basis of positional Kronecker product of *m* sets with power *n* as

$$\varphi\Pi r(m) * (\overline{1.n}) \Rightarrow R(m,n). \tag{12}$$

It can be represented as decomposition $R(m,n)$

$$R(m, n-m+1) \Rightarrow \sum_{\nu=1}^{m} \Psi(\nu, n-m+1) * Arang\{\varphi Perm * [\ \varphi Part(\nu) * m\ ]\}; \tag{13}$$

$$\Psi(\nu, k) \Rightarrow \varphi KC(\nu) * k; \tag{14}$$

$$\overline{\Psi(m,n)} \Rightarrow R(m, n-m+1) \oplus (\overline{0.m-1}). \tag{15}$$

The following relation is observed:

$$\overline{\Psi(m,n)} \Rightarrow \varphi KC(m) * (\overline{0.k}); \ k = n+m-1. \tag{16}$$

For the formation of the attached matrix of arbitrary order we use the system

$$\operatorname{Im} s(m,n) \Rightarrow \overline{\Psi(m,n)} \times \overline{\Psi(m,n)}\,. \tag{17}$$

This system is used as an argument set for the operator of formation positional graph structure [5]. It applied to find the algebraic complements of the matrix A on the basis of the operator $\varphi Dpv(\arg)$ [10].

$$\varphi Gr\left\{\left[\overline{\Psi(m,n)}\right]_r \times \left[\overline{\Psi(m,n)_L}\right]\right\} \Rightarrow \varphi Dpv\left\{\left[\overline{\Psi(m,n)}\right]_r \times \left[\overline{\Psi(m,n)_L}\right]\right\} * A\,. \tag{18}$$

The systems of coordinates are defined in the form of lexicographic Kronecker products in the form of vectors and matrixes. In them, the indices of rows r and columns L of the extracted sub-matrix are specified:

$$\operatorname{Im} s \Rightarrow R \times\circ K\,; \quad [R]_i \Rightarrow \bar{r}_i \quad [K]_j \Rightarrow \bar{L}_j\,. \tag{19}$$

In the given problem the relation $|\bar{r}| = |\bar{L}| = m$ is observed. The components of numerical sequences (16) are used as arguments of the operators. In particular, they can be used in operators of mapping into the index spaces $\bar{a} * \varphi Adres[\Psi(m,n)_i] \Rightarrow h_i$

Using (9), we shall find the Gramian matrix G (10) of the Fourier decomposition. We take into account that the elements of the matrix Z can be represented in the form:

$$[Z]_{rL} \Rightarrow \varphi Sum * \overline{(1.N)} * Arang(r+L)\,. \tag{20}$$

The SC model of positional Kronecker product of m elements $\overline{(1.N)}$ is determined taking into account

$$R(m,N) \Rightarrow \varphi Perm * \left\{ \sum_{\nu=1}^{m} \left\{ \begin{array}{l} \left[\varphi KC(\nu) * \overline{1.N-m+1}\right] * \\ * \, Arang(\varphi Perm * [Part(\nu) * m]] \end{array} \right\} \right\}. \tag{21}$$

For a uniform step Δx, the values (20) are determined from the product of polynomials. As the factors, their values are used:

$$f_r^{(n)}(k \cdot \Delta x) \Rightarrow \varphi Sum * \left[\bigcup_{i=0}^{n} \left[a_{ri} \cdot (k \cdot \Delta x)^i\right]\right];$$
$$f_L^{(n)}(k \cdot \Delta x) \Rightarrow \varphi Sum * \left[\bigcup_{i=0}^{n} \left[a_{Li} \cdot (k \cdot \Delta x)^i\right]\right]. \tag{22}$$

Their products we shall represent using the sequence (13).

$$Z_{rL} = f_r(\bar{x}^{(N)})^T \cdot f_L(\bar{x}^{(N)}) \Rightarrow \sum_{i=1}^{N} [f_r(\Delta x \cdot i) \cdot f_L(\Delta x \cdot i)];\ \bar{x}^{(N)} = [(1.\overline{N}) \cdot \Delta x]\,. \tag{23}$$

From here we have

$$Z_{rL} \Rightarrow \varphi Sum * \left[f_r(\overline{1.N}) \otimes f_L(\overline{1.N})\right]; k \in \overline{1.N}\,; \tag{24}$$

$$w_{r\,L}(x = i\cdot\Delta x) = f_r(x = i\cdot\Delta x)\cdot f_L(x = i\cdot\Delta x)\,. \tag{25}$$

The equation (24) is possible to represent as.

$$Z_{r\,L} \Rightarrow \sum_{i=1}^{N} w_{r\,L}(i\cdot\Delta x) \quad w_{r\,L}(i\cdot\Delta x) = f_r\,(i\cdot\Delta x)\cdot f_L(i\cdot\Delta x)\,. \tag{26}$$

In it, the values of coefficients of polynomial are used:

$$Z_{r\,L} = \sum_{i=1}^{N} [a_{r0} + a_{r1}(i\cdot\Delta x) + a_{r2}(i\cdot\Delta x)^2 + \cdots + a_{r\,n}(i\cdot\Delta x)^n]\times$$
$$\times[a_{L0} + a_{L1}(i\cdot\Delta x) + a_{L2}(i\cdot\Delta x)^2 + \cdots + a_{L\,n}(i\cdot\Delta x)^n] \Rightarrow \sum_{i=1}^{N} w_{r\,L}(i\cdot\Delta x). \tag{27}$$

In (27), the sums can be extracted as

$$q_{\,k} \Rightarrow \Delta x^k\cdot\beta_{\,k}\,;\quad \beta_{\,k} = \sum_{i=1}^{N} i^{\,k}\,. \tag{28}$$

In view of it, the equation (27) is possible to write down as

$$Z_{r\,L} = \sum_{i=0}^{2n} C(r,L)_i\cdot\beta_i\,(\Delta x)^i\cdot;\quad C(r,L)_i = f(\bigcup_{j=1}^{m}\overline{a}_j)\,. \tag{29}$$

SC model of vector of spectral coefficients

The sequences $\overline{\Psi(m,n)}$ are used in coordinate systems at the formation of algebraic complements of the elements of matrices. Applying the operator φDpv there is decomposition [5, 6, 8, 9]

$$\varphi Dpv(\arg) * R(m,N) \Rightarrow \varphi Perm * \left[\varphi Dpv(\arg) * \bigcup_{i=1}^{k}\theta_{\,i}\right];$$
$$\theta_{\,i} \in \varphi KC(m) * \left(\overline{1.N}\right);\; k = \left|\overline{\theta}\right|. \tag{30}$$

The distribution of degrees over the discrete poles for a fixed component of indices of columns is done by the rule

$$\varphi Dvp\left\{(\varphi Perm * \overline{r}^{(n)})\times\overline{L}^{(n)}\right\} * \widetilde{\theta}^{(m)} \Rightarrow \widetilde{\theta}^{(m)} * Arang\left[\left(\varphi Dvp * \overline{r}^{(n)}\right)\oplus\overline{L}^{(n)}\right]. \tag{31}$$

Using the properties of $\varphi Dpv(\arg)$ [1], we have

$$\varphi Dvp(\arg) * \left[G(m,n)\right] \Rightarrow \varphi Dvp(\arg) * \left[\varphi Perm * \Psi(m,n)\right]. \tag{32}$$

The coordinate vectors are used as arguments of the operators corresponding to the extracted sub-matrix

$$\varphi Dpv(\bar{r} \times \circ \bar{L}) * \tilde{\theta} \Rightarrow \left[\tilde{\theta} * Arang\left(\varphi Perm * \bar{r}\right)\right] \cdot \varphi \Pi r * \left[\tilde{\theta} * Arang(\bar{L})\right]. \tag{33}$$

As the indices of the degrees, the elements of coordinate components are used

$$\left(\overline{1.N}\right) * Arang(St); \quad St \Rightarrow \bar{r} \times \circ \bar{L}; \bar{r} \in \Psi(k,n); \bar{L} \in \Psi(k,n). \tag{34}$$

The coordinate components we shall represent as decompositions of regular fragments

$$\bar{r} \Rightarrow \varphi Part(1.s) * \tilde{r}^{(n)} \Rightarrow \bigcup_{i \in \overline{1.S}} z_j \oplus (1.k_i). \tag{35}$$

Then the algebraic complements of Z are determined with the help of the operators $\varphi Fg(\bigcup_i m_i)$ [2, 3]. In the given problem, such algorithm is realized on the basis of the operator $\varphi Dpv(\arg)$ applied to the components of the set

$$\varphi Dpv(\arg) * G(m, n+m-1) \Rightarrow \varphi Dpv(\arg) * \left\|\varphi Perm * \Psi(m,n)\right\| \Rightarrow$$
$$\Rightarrow \varphi Perm * \left[\varphi Dpv(\arg) * \Psi(m,n)\right]. \tag{36}$$

For the SC models of the inverse matrix, the operator $\varphi Fg(m_1, m_2)\ \Psi(v_1, m)_i \circ \Psi(m - v_1, m)_i = n$ is used. Therefore, it is possible to use the following forms of operators:

$$\varphi Part(2) * n \Rightarrow \bigcup_{i=0}^{n} (i.n-1) \quad \varphi Fg\left\{\bigcup_{i=0}^{n} (i.n-1)\right\} * \left[\overline{\Psi(i,n)} \otimes \overline{\Psi(n-i,n)}\right]. \tag{37}$$

The operators are applied to every component $\tilde{\theta} \in \Psi(n, N)$

$$\varphi Fg(ims) * \tilde{\theta} \Rightarrow \varphi \Pi r_{j \in \overline{1.S}} * \left\{\varphi \Pi r * \left(\tilde{\theta} * Arang(z_j)\right) \cdot FG(\tilde{\theta}_j)\right\}; \ \tilde{\theta}_j \in \overline{\Psi(m,N)}; \tag{38}$$

$$\varphi Dpv * \left[\tilde{\theta} * Arang(\varphi \Pr m * \bar{r})\right] \Rightarrow \varphi Sum * \{\left[\varphi Fg * \Psi(v_1,n)\right] \otimes$$
$$\otimes \left[\varphi Fg * \Psi(n - v_1, n)\right] \otimes \bar{\theta}_r\}. \tag{39}$$

This decomposition can be realized with the help of graph structures [5]

$$\varphi Gr((k_1, k_2) * \tilde{q}^{(n)} \Rightarrow \left[\varphi Dvp(\bar{r} \times \circ \bar{L}) * \overline{\Psi(k_1,n)}\right] \otimes$$
$$\otimes \left[\varphi Dvp(\bar{r} \times \circ \bar{L}) * \overline{\Psi(k_2,n)}\right]; \qquad k_1 + k_2 = n. \tag{40}$$

In view of the use of the positional principle, we shall get

$$\varphi Dvp\left\{(\varphi Perm * \bar{r}^{(n)}) \times \bar{L}^{(n)}\right\} * R(m,n) \Rightarrow$$
$$\Rightarrow Sum * \left\{\bigcup_i \Psi(m,n)_i * \varphi Arang\left[\varphi Perm * \bar{r}^{(n)})\right]\right\}. \tag{41}$$

The SC model for the algebraic complement *(r L)* of the element Gramian matrix G (3) we shall determine using the algorithm [1]

$$J_{rL} \Rightarrow \overline{\mu}_r^T \cdot Z \cdot \overline{\mu}_L ; \quad (42)$$

$$\overline{\mu}_r \Rightarrow \varphi Dpv\left\{\left(\overline{\Psi(m,n)}_r\right\}^* A^T ; \quad \overline{\mu}_L \Rightarrow \varphi Dpv\left\{\left(\overline{\Psi(m,n)}_L\right\}^* A ; \quad (43)$$

$$M \Rightarrow \varphi Dpv\left\{\left(\overline{\Psi(n,m)} \times \circ \overline{\Psi(n,m)}\right\}^* Z\right) . \quad (44)$$

The vector of spectral coefficients $\overline{\alpha} = f(\overline{\omega})$ is a function of the values of the matrix (42). Its multipliers are determined by the abovementioned algorithms

$$\overline{\omega} \Rightarrow \varphi Sum(i \in \overline{1.m}) * \left(\begin{bmatrix} \overline{\mu}_1 \otimes \overline{c} \\ \cdots \\ \overline{\mu}_i \otimes \overline{c} \\ \cdots \\ \overline{\mu}_m \otimes \overline{c} \end{bmatrix} \otimes M \right) ; \overline{c} = \begin{bmatrix} \overline{\mu}_1 & \overline{\mu}_2 & \cdots & \overline{\mu}_m \end{bmatrix} \cdot \overline{u} . \quad (45)$$

Here the summation of the elements by the columns is done. From here follows, that the algorithm for finding the vector of spectral coefficients has the form of a decomposition. Therefore, it has a parallel structure and can be used in computers working in the modes of parallel calculation.

Conclusions

In the derived analytical expression for the inverse matrix of the equation system, the vector of the degrees of the argument step is allocated in the direct form. This vector can be allocated and calculated independently, so it is expedient for not entering into the overall computing process. Such approach can be used as a regularization method for maintaining the numerical stability of the algorithm and preventing the degenerate situations.

The application of the method of SC models allows developing the algorithms of polynomial approximation in the form of decomposition. It allows applying them in computers working in the modes of parallel calculations.

The obtained algorithm possesses the properties of recursivity and it allows applying economic methods of programming. Efficiency of the received algorithms has been verified up by a numerical experiment for the case of polynomial approximation using Hilbert matrix, which is the standard of bad conditionality. It is believed, that finding the inverse matrix, with order greater than 10^{th}, is impossible. The developed results have allowed finding the 20^{th} order inverse matrix with the 100% accuracy.

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G. Burovs. Skaitliski stabils simbolisks kombinatoriskais polinomiālās aproksimācijas modelis identifikācijas un imitācijas modelēšanas problēmām
Rakstā apskatīta analogo tehnisko objektu identifikācijai izmantoto eksperimentālo datu aproksimācija izmantojot patvaļīgas formas polinomiālas funkcijas. Simbolisko kombinatorisko modeļu izmantošana ļāva analītiskā formā iegūt algoritmu vienādojumu sistēmu matricu, kas veidotas no šādām funkcijām, invertēšanai. Tas ļauj izmantot netradicionālās algoritmu regularizācijas metodes un palielināt to noturību pret trokšņu iedarbību. Iegūti teorētiskie rezultāti, kas ļauj tiešā veidā izdalīt faktorus, kas noved pie deģenerētu situāciju rašanos. Tas ļauj skaitļošanas procesu padarīt novērojamu un koriģēt tā īpašības. Problēma tika risināta ņemot vērā algoritmu izmantošanu modernajos datoros, kas darbojas paralēlos skaitļošanas režīmos. Algoritma darbība tika pārbaudīta ar skaitlisku eksperimentu, kas pierādīja tā efektivitāti. Ar 100% precizitāti tika aprēķināta 20.kārtas inversā Hilberta matrica, izmantojot to polinomiālai aproksimācijai. Tiek uzskatīts, ka iegūt šādu rezultātu matricām ar kārtu lielāku par 10 nav iespējams.

G. Burov. Numerically stable symbolical combinatory model of polynomial approximation for problems of identification and imitation modelling
The problem of the approximation of experimental data for identification of analog objects with the help of polynomial functions of any kind is considered. The application of symbolical combinatory models has allowed creating an algorithm for inverting the matrices of the equation systems made of such functions, in the analytical form. It allows to apply non-conventional methods of algorithm regularization and to increase their noise tolerance. The theoretical results, allowing allocating, in the direct form, the factors leading to degenerate situations, are developed. It allows to make computing process observable and to correct its properties. The problem was solved, taking into account the application of algorithms in modern computers working in the modes of parallel calculation. The validity of the algorithm has been verified by a numerical experiment and its efficiency is proved. Hilbert's inverse 20th order matrix, used for polynomial approximations has been calculated with the 100% accuracy. It is believed, that obtaining such result for the matrices with the order greater than 10th is impossible.

Г. Буров. Численная устойчивость символьной комбинаторной модели полиномиальной аппроксимации для задач идентификации и имитационного моделирования

Решена задача аппроксимации экспериментальных данных идентификации аналоговых объектов с помощью полиномиальных функций произвольного вида. Применение символьных комбинаторных моделей позволило получить алгоритм обращения матриц систем уравнений, составленных из таких функций, в формульном виде. Это позволяет применить нетрадиционные методы регуляризации алгоритмов и повысить их помехоустойчивость к шумам. Получены теоретические результаты, позволяющие в явном виде выделить факторы, приводящие к вырожденным ситуациям. Это позволяет сделать вычислительный процесс сделать наблюдаемым и корректировать его свойства. Задача решалась из условий применения алгоритмов для решения в современных ЭВМ, работающих в режимах параллельных вычислений. Работоспособность алгоритма была проверена численным экспериментом и доказана его эффективность. Была рассчитана со 100% точностью обратная матрица Гильберта 20 порядка, применяемая для полиномиальной аппроксимации. Считается, что получить такой результат для матриц, имеющих порядок выше 10 -го невозможно.