Constantin Popa

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IN MEMORIAM CONSTANTIN POPA

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Abstract This article is dedicated to Professor Constantin Popa - math teacher, professor, researcher, colleague, and friend. Our goal is to present some of the most important aspects of his scientific activity, as well as some traits that made both him a remarkable scientist and colleague, with high standards of professionalism. He published papers on preconditioning techniques for finite element method and finite differences discretizations for boundary value problems, iterative methods for least-squares problems for linear systems of equalities and inequalities (projection algorithms, esp. Kaczmarkz-like algorithms), algebraic reconstruction techniques in computerized tomography, inverse problems regularization techniques and methods for approximating the minimal norm solution of first-kind integral equations.

1. SHORT CV

Born on October 10, 1956 in Bucharest, Constantin Popa was one of the two children of Steliana-Marioara and Victor Popa. He attended "Ion Neculce" High school of Bucharest between 1971 and 1975. During 1976-1981 he got a Bachelor of Science in Mathematics from University of Bucharest. Professor Ion Colojoară noticed him as being a student "of 10" from the very first lectures he delivered to that class. Besides this, Constantin was also a good rugby player for A.S. *Sportul Studenţesc*. Also, a player "of 10" as it was mentioned by Prof. Colojoară in a note from a student newspaper. Driven by the passion for mathematics, Constantin got employed as a teacher on mathematics at Elementary school 107, Bucharest, between 1981-1984.

Afterwards, he went to National Institute for Scientific and Technical Creation (INCREST), Bucharest as a mathematician. Since 1984, his activity as a programmer and mathematician within the INCREST Computing Center was elaboration of algorithms and deploying them into calculation programs for problems related to the structure and aerodynamics of airplanes. He participated (as a founding member) in the Scientific Seminar "Multigrid Methods and Applications", organized by the mathematics team of INCREST, led by Eugen Soos. He gave talks on iterative methods, multigrid method, distributions, Sobolev spaces, and other topics in the field of numerical methods.

Furthermore, he followed a scientific researcher position at Institute for Electrical Engineering (ICPE) from Politehnica University of Bucharest, starting from 1987. Here, until 1989, he collaborated both in the research contracts of the team, in nonlinear optimization problems and nonlinear differential equations, as well as with researchers and professors from the Politehnica University on finite element and boundary element methods with complex functions, and the approximation of solutions of nonlinear and non-autonomous differential equations. In 1990 he got a lecturer position at Ovidius University of Constanţa (OUC) where he will carry out his didactic activity for the rest of his life. In 1995 he completed his PhD studies on Numerical Analysis at the University of Bucharest under the supervision of professor Dorel Homentcovschi. His PhD topic was about preconditioning and multigrid techniques for accelerating the convergence of some classes of iterative methods. Since 2000 he has been awarded with a full professor position on Applied Mathematics at the Faculty of Mathematics and Computer Science from Ovidius University of Constanţa. Meanwhile, since 2001 on, he also held a position of scientific researcher at "Gheorghe Mihoc - Caius Iacob" Institute of Mathematical Statistics and Applied Mathematics of Romanian Academy from Bucharest. He has also supervised more PhD students, starting with 2008. As a researcher, he published several textbooks and more than 90 papers in renowned journals, being cited for more than 800 times; he is the holder of 5 DAAD research grants (minimum 2 months, esp in Germany) and the holder of 2 postdoctoral grants of one year (Israel and Germany). Constantin also had multiple visiting professor positions (in Germany), was a member of the editorial board for some journals, peer reviewer of international ones, member of national and worldwide professional scientific organizations; he gave more than 30 talks as an invited speaker at universities from Germany, Sweden, Hungary, he participated in more than 60 conferences abroad, he is co-editor to 10 international conference proceedings, and he was the president of organizing committees for internationational conferences.

Beside these, Constantin held administrative and managerial positions within faculty, university, and national scientific society. Therefore, he was Head of Chair of Computer Science and Numerical Methods between 1998-2012, Director of Doctoral School of Applied Sciences of OUC in 2013-2014, vice-Rector for Research between 2014-2016, vice-President of Romanian Society of Industrial and Apllied Mathematics (ROMAI) for 2017-2020, and Director of Doctoral School of Mathematics of OUC between 2018-2020.

For many generations of students, master and doctoral students, whose steps he guided with passion, determination and professionalism, in his 30 years of activity at the Ovidius University of Constanţa, Constantin Popa will be remembered as a dedicated mentor, a standard of seriousness and modesty.

He left this world on November 23, 2020, after having fought a strong illness.

2. SCIENTIFIC CONTRIBUTIONS

It is not our intention to provide the reader with an exhaustive review of all work for Professor Constantin Popa. An almost complete list of all his published papers and books is given at the end of this presentation, so one can have an image of his work. Here we shall review some topics that we appreciate being among professor Popa's favorite ones.

2.1. PRECONDITIONING TECHNIQUES

Consider the linear partial differential equation

$$Lu = f \tag{1}$$

defined on a real Hilbert space H with the operator L bounded and H-elliptic. The discretization of equation (1) leads to the linear algebraic system,

$$Ax = b. \tag{2}$$

In almost all situations, matrix A is large and sparse. For this reason, iterative methods are widely used to solve efficiently system (2).

The convergence rate of iterative methods applied to system (2) depends on the spectral properties (eigenvalues distribution) of matrix A. The convergence is fast for clustered eigenvalues and slow for scattered eigenvalues. Unfortunately, the spectrum of matrix A is scattered and depends on the discretization parameter.

Multigrid (MG) and preconditioned generalized conjugate gradient (PGCG) are the iterative methods that have the best performances in solving system (2). MG methods have an optimal order of convergence, i.e. the amount of work and storage is proportional to the number of unknowns. The convergence rate of the PGCG methods depends on the preconditioning.

The preconditioning transforms system (2) into a new system. This transformation consists of multiplying system (2) with a matrix named preconditioning matrix. The preconditioned system must be as easy to solve as system (2).

Denote the preconditioning matrix by P. There are three ways to apply the preconditioning, i.e.:
- right-preconditioning

$$Ax = b \Leftrightarrow \tilde{A}_1\tilde{x_1} = \tilde{b}_1, \text{ with } \tilde{A}_1 = AP^{-1}, \; x_1 = Px, \; \tilde{b}_1 = b \tag{3}$$

- left-reconditioning

$$Ax = b \Leftrightarrow \tilde{A}_2\tilde{x}_2 = \tilde{b}_2, \text{ with } \tilde{A}_2 = P^{-1}A, \; \tilde{x}_2 = x, \; \tilde{b}_2 = P^{-1}b \tag{4}$$

- split- preconditioning

$$Ax = b \Leftrightarrow \tilde{A}_3\tilde{x}_3 = \tilde{b}_3, \text{ with } \tilde{A}_3 = \Gamma^{-1}A\Gamma^{-T}, \; \tilde{x}_3 = \Gamma^T x, \; \tilde{b}_3 = \Gamma^{-1}b \tag{5}$$

where

$$P = \Gamma\Gamma^T \tag{6}$$

The influence of the preconditioning on the solution of linear systems is usually quantified by the comparison between the eigenvalues distribution of the preconditioned and non-preconditioned system matrix, respectively. Consider that finite element method was used to obtain system (2) from equation (1) and denote by G the Gram matrix of the finite element basis. The Cholesky decomposition of the Gram matrix reads as $G = CC^T$. The spectral condition number of the matrix $\tilde{A} = C^{-1}AC^{-T}$ is independent on the discretization parameter. Under these assumptions, the convergence rate of PGCG preconditioned with the Cholesky factors of the Gram matrix is mesh independent. Unfortunately, in many practical applications, due to the structure of the Gram matrix, the computational effort of the preconditioning is almost the same as that for solving system (2).

Denote by $G = M - N$ an incomplete factorization of the Gram matrix with M a symmetric, positive definite matrix. This decomposition always exists because G is always symmetric and positive definite. In references [1] and [2] it is proved that if $r = \rho(M^{-1}N) < 1$ ($\rho(A)$ being the spectral radius of the matrix A), the spectral condition number of the matrix $\tilde{A} = \hat{M}^{-1/2}A\hat{M}^{-1/2}$ with $\hat{M} = M(I - B^k)^{-1}(I - B)$, $B = M^{-1}N$ obtained from preconditioning the linear system (2) by $k \geq 1$ steps of the iterative method $z^{j+1} = (M^{-1}N)z^j + M^{-1}y$ is mesh independent if r is mesh independent. It must be mentioned that the preconditioning by Gram matrix approximations is not related to the system matrix and it is suitable for parallel computation.

The results from [20]-[21] are generalized to non-linear systems in [6]. For non-linear systems, PGCG is the linear solver used in the non-linear Newton / Picard iterations. The non-linear systems considered in [6] are the discretization of non-linear, elliptic, partial differential equations. It is proved in [6] that the Newton iteration of the preconditioned system converges to the exact solution of the discrete equation. Note that the preconditioning by Gram matrix approximations defined in [6] is a Newton-free method.

The numerical experiments performed in [22]-[5] and [7]-[9] show that the preconditioning developed theoretically in [20], [21], [6] is robust, efficient and suitable to solve numerically linear and non-linear partial differential equations.

2.2. NUMERICAL METHODS IN PHYSICAL SCIENCES

2.2.1 Multi component Mixtures. The diffusion law for an n - component mixture, also known as generalized Fick law, is:

$$J_i = -\rho \sum_{k=1}^{n-1} D_{ik} \nabla c_k, \tag{7}$$

where J_i are the diffusion flows (counted with respect to the barycentric motion), c_k is the mass fraction of component k, ρ is the mass density of the mixture and D_{ik} is the $(n-1)^2$ diffusion coefficients tensor corresponding to the reference velocity.

The mathematical model for the mass transfer in multi-component mixtures is a system of strongly coupled second order elliptic / parabolic partial differential equations (PDE). Mathematical solutions for multi-component mass transfer in complex situations are not very plentiful. The main aim of the articles published on this topic was the numerical solution of a particular problem.

A general strategy to analyse the numerical solving of the 2D, steady-state, linear and non-linear multi-component mass transfer equations was proposed in [10] - [13] . This strategy consists of:
- to emphasize very clearly the influence of the cross-diffusion coupling and the number of chemical species involved in the process on the convergence rate of the numerical algorithms;
- to test multigrid (MG) methods for numerical solving the multi-component mass transfer problems;
- to develop specific preconditioners for multi-component mass transfer problems, which will be used in connection with the gradient-type and Krylov subspace methods (BICGSTAB and restarted GMRES(m)); the nonlinear algorithm employed in this case is the modified Picard iteration.

The test problems used are the dimensionless diffusion-reaction equations that model the mass transfer accompanied by an isothermal, first order, complex chemical reaction inside a finite slab catalyst pellet with square section of length L,

$$\sum_{j=1}^{4} \left(\frac{\partial}{\partial x} D_{ij} \frac{\partial Z_j}{\partial x} + \frac{\partial}{\partial y} D_{ij} \frac{\partial Z_j}{\partial y} \right) + R_i = 0, i = 1, \ldots, 4 (x,y) \in \Omega = (0,1) \times (0,1) \tag{8}$$

$(x,y) \in \Omega = (0,1) \times (0,1)$, with the boundary conditions:

$$Z_1 = 1, Z_1 = 0, i = 2,3,4, \; (x,y) \in \partial\Omega \tag{9}$$

and the convection-diffusion reaction equations that describe the steady, 2D, laminar flow of an incompressible fluid inside a slot of thickness d and length L accompanied by an isothermal, first order, complex chemical reaction,

$$\varepsilon Peu(y)\frac{\partial Z_i}{\partial x} = \sum_{j=1}^{4}\left(\varepsilon^2 \frac{\partial}{\partial x} D_{ij}\frac{\partial Z_j}{\partial x} + \frac{\partial}{\partial y} D_{ij}\frac{\partial Z_j}{\partial y}\right) + R_i, i = 1, \ldots, 4 \quad (10)$$

$(x, y) \in \Omega = (0, 1) \times (0, 1), u(y) = \frac{1}{2}(y - y^2), \varepsilon = \frac{d}{L}, P_e = \frac{U_0 d}{D_{ref}}$
with the boundary conditions

$$x = 0, Z_l = 1, z_i = 0, i = 2, 3, 4 \quad (11)$$

$$x = 1, J_i = 0, i = 1, \ldots, 4 \quad (12)$$

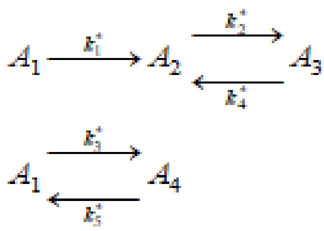
$$y = 0, J_i = 0, i = 1, \ldots, 4 \quad (13)$$

$$y = 1, j_i = 0, i = 1, \ldots, 4 \quad (14)$$

where

$$J_i = \sum_{j=1}^{4} D_{ij}\frac{\partial Z_j}{\partial x}, or J_i = \sum_{j=1}^{4} D_{ij}\frac{\partial Z_j}{\partial y}, i = 1, \ldots, 4 \quad (15)$$

is the mass diffusion flux of the ith species with respect to the mass average velocity.
The chemical reactions considered are:



In the previous relations R_i are the chemical reaction rates defined by,
$R_1 = -k_1 Z_1 - k_3 Z_1 + k_5 Z_4, R_2 = k_1 Z_1 - k_2 Z_2 + k_4 Z_3,$
$R_3 = k_2 Z_2 - k_4 Z_3, R_4 = k_3 Z_1 - k_5 Z_4,$
$Z_i = A_i / A_{1b}$ are the dimensionless concentrations, A_{1b} is the bulk molar concentration of species A_1 (for equation (8) or the mass concentration of species A_1 at the slopt inlet, i.e. $x = 0$, (for equations (4)), $k_i = k_i^* L^2 / D_{ref}$ are the non - dimensional reaction rate constants for equations 8) and $k_i = d^2 / D_{ref}$ are the non - dimensional reaction rate constants, D_{ij} are the multi-component

Fick diffusion coefficients related to D_{ref} and D_{ref} is a reference diffusion coefficient.

The mathematical models previously presented represent the non-linear test problems used in [10] - [13] (the diffusion coefficients depend on the concentration values). The linear test problems were obtained from the non-linear ones by considering the multi-component Fick diffusion coefficients constants. The computation of the diffusion coefficients is presented in [12] and[13] . The finite difference method was used to discretize the mathematical model equations. The nonlinear algorithms used are the modified Picard iteration and MG.

The linear system that should be solved in a Picard step or for the linear test problem can be written as

$$AU = B, \tag{16}$$

where

$$A = \begin{bmatrix} A_{11} & A_12 & A_{13} & A_{14} \\ A_{21} & A_22 & A_{23} & A_{24} \\ A_{31} & A_32 & A_{33} & A_{34} \\ A_{41} & A_42 & A_{43} & A_{44} \end{bmatrix}, Z = \begin{bmatrix} Z_1 \\ Z_2 \\ Z_3 \\ Z_4 \end{bmatrix}, B = \begin{bmatrix} b^1 \\ b^2 \\ b^3 \\ b^4 \end{bmatrix}, \tag{17}$$

In [12] a preconditioning technique based on a single block diagonal preconditioner was designed and the spectra of the system matrix blocks after the preconditioning was analysed. The preconditioners tested are the block diagonal matrices

$$A = \begin{bmatrix} \tilde{\Delta_0} & 0 & 0 & 0 \\ 0 & \tilde{\Delta_0} & 0 & 0 \\ 0 & 0 & \tilde{\Delta_0} & 0 \\ 0 & 0 & 0 & \tilde{\Delta_0} \end{bmatrix}, \tag{18}$$

where $\tilde{\Delta_0}$ is the complete / incomplete Cholesky factorization (symbolized by CC /IC) of the discrete Laplace operator. The conclusion was that for both, diagonal and off-diagonal preconditioned blocks, a mesh independent condition number was obtained. Unfortunately, similar theoretical results involving the eigenvalues of the whole system matrix could not be obtained, but the numerical experiments from [10] -[13] show practically the efficiency of the preconditioning technique used.

One of the widely used methods to solve parabolic PDE, the splitting method, was not employed until now in solving multi-component mass transfer equations. In [14] and[15] a new splitting method designed for multi-component mass transfer equations was presented and analysed.

Consider the following linear governing equations expressing conservation of the chemical species in the absence of chemical reactions for multi-component mixture with n chemical species (the mass density of the mixture is considered constant):

$$\frac{\partial c_1}{\partial t} + v\ grad\ c_1 = \sum_{k=1}^{n-1} D_{1k}\delta c_k$$

$$\cdots\cdots\cdots\cdots$$

$$\frac{\partial c_{n-1}}{\partial t} + v\ grad\ c_{n-1} = \sum_{k=1}^{n-1} D_{n-1,k}\Delta c_k \tag{19}$$

where c_k is the mass concentration of component k, v is the velocity vector and Δ is the Laplace operator.

The discretization of the spatial derivatives from 19 leads to

$$\frac{\partial c_1}{\partial t} + \Lambda_h c_1 = \sum_{k=1}^{n-1} D_{1,k}\Delta_h c_k$$
$$\cdots\cdots\cdots$$
$$\frac{\partial c_{n-1}}{\partial t} + \Lambda_h c_{n-1} = \sum_{k=1}^{n-1} D_{n-1,k}\Delta_h c_k \tag{20}$$

where Δ_h and Λ_h are the discrete Laplace and convection operator, respectively. The splitting technique was analyzed in [14] and [15].

The main advantage of this splitting is: if an implicit or semi-implicit (Crank - Nicholson) time integration method is used, the algebraic system that should be solved is block triangular. Obviously, if Δ_h and Λ_h are multi-dimensional spatial operators, further splitting of the previous matrices into one dimensional spatial operators can be made. Therefore, the blocks of the block triangular matrices are tri-diagonal matrices.

Compared to the classical types of operator splitting, i.e. geometric splitting (a multi-dimensional spatial operator is split into a sum of one-dimensional operators) and physical splitting (the spatial operator is split into different physical terms such as diffusion terms, convection and reaction terms), the splitting algorithm from [14] and[15] can be viewed as an algebraic splitting, i.e. the spatial operator is split into simpler algebraic matrices following only algebraic reasons.

Theoretically, it was proved in [14] that, for a n- dimensional matrix, the lower and upper triangular factors are positive definite, which ensures the convergence of the splitting algorithm. For the particular case of ternary systems

(2 x 2 blocks matrix) and Dirichlet boundary conditions, the convergence of the splitting algorithm is proved in [15]. Also, the numerical experiments made in [14]-[15] confirm the stability and accuracy (second order in space and time) of the algorithm.

3. POROUS MEDIA

Richards equation (RE) is the widely used mathematical model for water flow in variably saturated porous media. RE models the flow in porous media of a wetting fluid (water) in the presence of a non-wetting fluid (air) assumed to be at constant pressure. Numerical approximations are usually used to obtain the solution of the RE because, RE is a highly nonlinear, possibly degenerate, parabolic differential equation.

A wide range of numerical techniques in a variety of ways were tested for the numerical solution of RE. However, the MG method, one of the most powerful method for solving nonlinear PDE, was not used to solve 2D (3D) transient RE. An effort to overcome this fact was made in [16] and[20] . The transient water infiltration into unsaturated soils using the dimensionless water content as unknown for RE was analysed in [16], [19]. The soil models employed in [16], [19]. are Broadbridge -White and van Genuchten- Mualem. The numerical results obtained in[16] and[19] show good numerical performances for the nonlinear MG algorithm.

The pressure head - based form of RE and the van Genuchten - Mualem soil model were used in [20] for the case of transient saturated - unsaturated flow. The modified Picard preconditioned conjugated gradient (Krylov subspace) method was also tested in [20]. The numerical results obtained in [20] show that the convergence rate of the two algorithms is comparable. However, the mesh behaviour of the convergence rate of MG is slightly superior to that of the modified Picard method. Also, the mesh behaviour of the efficiency of the nonlinear MG algorithm is excellent. On very fine grids (257 - 513 grid points) the nonlinear MG is approximately ten times faster than the modified Picard iteration.

Only few articles considered flow around solid inclusions embedded in a porous medium. For the flow past an impervious cylinder embedded in a fluid saturated porous medium only the linear (Darcy and Darcy - Brinkman) models were used. In [21], the flow past an impermeable cylinder embedded in a fluid saturated porous medium was studied numerically considering valid a nonlinear model (the Brinkman-Forchheimer-Darcy or Brinkman-Hazen-Dupuit-Darcy model). The flow is viscous, laminar, steady and incompressible. The porous medium is isotropic, rigid and homogeneous. The stream function - vorticity equations were solved numerically in cylindrical coordinates system. The influence of the cylinder Reynolds number, Darcy number and Forchheimer term on the velocities field and surface pressure was investigated for two boundary conditions on the surface of the cylinder: slip and no - slip.

3.1. BIFURCATIONS

A numerical continuation algorithm for bifurcation problems of 2D nonlinear elliptic equations (simple turning points and Hopf bifurcation points) based only on iterative methods (Preconditioned Generalized Conjugate Gradient, PCGC and MG) is presented in [22]. PGCG acts as coarse grid solver in the MG cycle. The test problems selected are the mathematical models of the non-isothermal catalyst pellet and Lengyel-Epstein model of the CIMA reaction. The numerical experiments show that algorithm proves to be efficient and reliable.

3.2. PROJECTION ALGORITHMS WITH CORRECTION

In terms of projection algorithms with correction professor Popa considered two versions of a general correction procedure applied to a classical linear iterative method. This leads, under certain assumptions, to obtain an extension of it to in-consistent linear least-squares problems. In the article [24] authors proved that some well known extended projection type algorithms from image reconstruction in computerized tomography into one or the other of these general versions and are derived as particular cases of them. In the paper the authors present some numerical experiments on two phantoms widely used in image reconstruction literature. The experiments done using extended Kaczmarz-like algorithms (Kaczmarz Extended with Relaxation Parameters, mixed Kaczmarz - Conjugate Gradient, and Cimmino extended) in [24] show the importance of these extension procedures, rejected in the quality of reconstructed images.

3.3. IMAGE RECONSTRUCTION

Algebraic reconstruction techniques (ARTs), on both their successive and simultaneous formulations, have been developed since the early 1970s as efficient row-action methods for solving the image-reconstruction problem in computerized tomography. In this respect, two important development directions were concerned with, first, their extension to the inconsistent case of the reconstruction problem and, second, their combination with constraining strategies, imposed by the particularities of the reconstructed image.

In the paper [30], professor Popa and the authors introduced extending and constraining procedures for a general iterative method of an ART type and they proposed a set of sufficient assumptions that ensure the convergence of the corresponding algorithms.

As an application of this approach, they proved that Cimmino simultaneous reflection method satisfies this set of assumptions, and also derived extended and constrained versions for it.

Numerical experiments with all these versions are presented in [30] on a head phantom widely used in the image reconstruction literature.

3.4. REGULARIZATION TECHNIQUE FOR KOVARIK-LIKE APPROXIMATE ORTHOGONALIZATION ALGORITHMS

In the paper [25] professor Popa Constantin and authors considered four versions of Kovarik iterative orthogonalization algorithm, for approximating the minimal norm solution of symmetric least squares problems.

Although the theoretical convergence rate of these algorithms is at least linear, in practical applications we observed that a too big number of iterations can dramatically deteriorate the already obtained approximation. In this respect the authors analysed the above mentioned Kovarik-like methods according to the modifications they make on themachine zero eigenvalues of the problem (symmetric) matrix.

In [25] authors established a theoretical almost optimal formula for the number of iterations necessary to obtain an enough accurate approximation, as well as to avoid the above mentioned troubles. Experiments on collocation discretization of a Fredholm first kind integral equation illustrate the efficiency of these considerations.

4. ALGORITHMS FOR IMAGE RECONSTRUCTION IN COMPUTERIZED TOMOGRAPHY

Computerized Tomography (CT) imaging, also known as "CAT scanning" (Computerized Axial Tomography), has been used primarily in medical applications, like guided biopsy, minimally invasive therapy, tumours detection, blood clots and blood vessel defects, radiotherapy cancer treatments and orthopaedic medicine and imaging of bony structures. It has also extremely important applications in industrial real world problems, like metrology. A CT imaging system produces cross-sectional images or "slices" of anatomy, like the slices in a loaf of bread. These cross-sectional images are then backwards reconstructed (or "back projected") by a dedicated computer into a two-dimensional image of the "slice" that was scanned.

From the view point of its mathematical model, the CT image reconstruction problem can be formulated as follows: let $D \subset \mathbb{R}^2$ be a bounded domain and $f : D \longrightarrow \mathbb{R}^2$ a function such that we know the value of the line integral $\int_{AB\cap D} f(s)ds$ for any line AB in $\mathbb{R}^2$; then, can we find the values $f(x,y)$, for any point $(x,y) \in D$?. The problem was solved as a mathematical problem by Johann Radon in 1917, who provided a formula on which the filtered back projection method for reconstructing the CT images, that is implemented in almost all the CT devices, has been developed.

In an alternative method, called Algebraic Reconstruction Technique (ART), the CT image reconstruction problem is discretized and transformed into a system of linear equations

$$Ax = b, \tag{21}$$

where A is an $m \times n$ (real) matrix and $b \in \mathbb{R}^m$. Usually, A is a (very) large matrix, and also (very) sparse. Unfortunately, due to errors induced by contin-

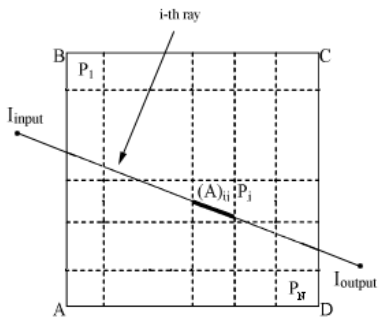


Fig. 1. Construction of the scanning matrix

uous mathematical modelling assumptions, discretization and measurements errors, the discrete ART mathematical model is no longer a consistent system of linear equations as (21), and it must be reformulated as a linear least squares problem: find $x \in \mathbb{R}^n$ such that

$$\| Ax - b \| = \min\{\| Az - b \|, \ z \in \mathbb{R}^n\}, \tag{22}$$

where $|| \cdot ||$ is the Euclidean norm.

This is this domain where Prof. Constantin Popa has contributed in a substantial way, by proposing several algorithms which can rise the efficiency and robustness of classical projection-based algorithms (as Kaczmarz and Cimmino type algorithms) for algebraic reconstruction of CT images. We present below the main results he has obtained along the years.

Professor Constantin Popa and his research team considered the inconsistent case of (22), i.e. $P_{\mathcal{N}}(A^T) \neq 0$. They introduced the Extended KT (EKT), EKT with Relaxation Parameters (EKTRP) and Extended Cimmino (ET) algorithms, which are extensions of the algorithms Kaczmarz and Cimmino projection methods for consistent systems of linear equations to inconsistent linear least squares problems, and proved their convergence.

Algorithm (EKT)
Initialization: $y^0 = b, x^0 \in \mathbb{R}^n$
Iterative step:

$$\begin{array}{rcl} y^{k+1} & = & \varphi_1 \circ \cdots \circ \varphi_n(y^k), \\ b^{k+1} & = & b - y^{k+1}, \\ x^{k+1} & = & \Phi_1 \circ \cdots \circ \Phi_m(b^{k+1}; x^k), \quad k \geq 0. \end{array} \tag{23}$$

Algorithm (EKTRP)
Initialization: $x^0 \in \mathbb{R}^n, y^0 = b$
Iterative step:

$$\begin{array}{rcl} y^{k+1} & = & \varphi_1 \circ \cdots \circ \varphi_n(\alpha; y^k); \\ b^{k+1} & = & b - y^{k+1} \\ x^{k+1} & = & P^{\omega}_{H_1} \circ \cdots \circ P^{\omega}_{H_m}(b^{k+1}; x^k), \quad k \geq 0. \end{array} \tag{24}$$

Algorithm Extended Cimmino (EC).
Initialization: $\alpha_i > 0, \omega_i > 0, \alpha = \sum_{j=1}^{n} \alpha_j, \omega = \sum_{i=1}^{m} \omega_i, y^0 = b, x^0 \in \mathbb{R}^n$
Iterative step:

$$\begin{array}{rcl} y^{k+1} & = & y^k - \frac{2}{\alpha} \sum_{j=1}^{m} \omega_j \frac{\langle y^k, A^j \rangle}{\|A^j\|^2} A^j, \\ b^{k+1} & = & b - y^{k+1} \\ x^{k+1} & = & x^k - \frac{2}{\omega} \sum_{i=1}^{m} \omega_i \frac{\langle x^k, A_i \rangle - b_i^k}{\|A_i\|^2} A_i, \quad k \geq 0. \end{array} \tag{25}$$

Following the observation that using oblique projections would get an (asymptotic) acceleration of convergence and an enough good approximation of a solution in only few iterations, the algoritm Kaczmarz with Oblique projections algorithm (KO) was proposed, and the convergence result for the algorithm KO in the consistent case of the problem (22) was given.

Algorithm KO. *Initialization:* $x^0 \in \mathbb{R}^n$
Iterative step:

$$x^{k+1} = P^D_{H_1} \circ \cdots \circ P^D_{H_m}(x^k), \quad k \geq 0. \tag{26}$$

We will first connect this algorithm with a reformulation of the problem (22) as

$$\| \bar{A}\bar{x} - b \| = \min\{\| \bar{A}z - b \|, z \in \mathbb{R}^n\}, \text{ where } \bar{A} = AD^{-\frac{1}{2}}. \tag{27}$$

For further details, see [33], [34], [30], [26].

Various constraining strategies for improving the reconstruction were given ([32], [31], [28],[36]), together with some considerations about possible "hybrid" type projection algorithms: Kaczmarz with Conjugate Gradient [35], Kaczmarz with various Genetic type algorithms ([27]), Kaczmarz as a direct solver ([29]).

4.1. ITERATIVE ALGORITHMS FOR INCONSISTENT SYSTEMS OF LINEAR INEQUALITIES

Let us consider the following system of linear inequalities

$$Ax \leq b \tag{28}$$

where $A \in \mathbb{R}^{m \times n}, b \in R^m$.

Solving system (28) is fundamental in linear optimization problems, especially for those of reconstruction of computed tomography images, and can be done in two ways. The first way consists in transforming the system into a convex programming problem and then applying direct methods for finding the solution. There are some limitations of these methods, due to the inconsistency of the system, its large size $\{m, n \geq 10^5\}$ or to the fact that the matrix A is rare and ill-conditioned. A second way of solving system (28) involves using iterative methods, which don't consist of complex matrix calculation techniques, implementation steps being simple and relatively easy to program. Starting from 2013, Constantin Popa, together with Doina Carp and Cristina Serban, published several papers, a chapter and a book, regarding the latter direction, performing a thorough study of a special type of iterative algorithms designed to solve the inconsistent (incompatible) system (28) in a least squares sense. This research was the one on which the doctoral thesis of Cristina Serban, mentored by prof. Constantin Popa, was based on.

The whole study is based on the iterative algorithm designed by S.P. Han and described in *Least squares solution of linear inequalities*, Tech. Rep. TR-2141, 1980 (algorithm **H**), the first in its class of algorithms specifically developed for efficiently approximating least squares solutions of inconsistent systems of linear inequalities, this problem being formulated as follows: determine $x^* \in \mathbb{R}^n$ such that

$$\frac{1}{2} \parallel (Ax - b)_+ \parallel^2 = \min! \tag{29}$$

where

$$((Ax - b)_+)_i = \max\{(A_i x - b_i), 0\}, i = 1, \ldots, m \tag{30}$$

Having $x^0 \in \mathbb{R}^n$ an initial datum, at each iteration, $k = 0, 1, \ldots$, the algorithm **H** consists of three steps:

Step 1. Find $I_k = I(x^k) = \{i | A_i^T x^k \geq b_i\}$ and compute $d^k \in \mathbb{R}^n$ as the (unique) minimal norm solution of the linear equalities least squares problem

$$\parallel A_{I_k} d - (b_{I_k} - A_{I_k} x^k) \parallel = \min! \tag{31}$$

Step 2. Compute $\lambda^k \in \mathbb{R}$ as the smallest minimizer of the function

$$\theta(\lambda) = f(x^k + \lambda d^k), \lambda \in \mathbb{R}. \tag{32}$$

Step 3. Set $x^{k+1} = x^k + \lambda^k d^k$
The descent direction d^k in **Step 1** is computed by Han using the singular value decomposition (SVD).

The research team considered the cases of the algorithms Generalized Han (**GH**), Regularized Han (**RH**) and Modified Han (**MH**), which are called of type Han because they are designed with the same structure as the one of the Han's algorithm. The first two algorithms were introduced by Bramley and B. Winnicka (1994), and K. Yang (1990), respectively. The algorithm **MH** was proposed by the research team, the results of this work being published in [42] and [44].

The Han-type algorithms differ at Step 1, the calculation of the descent direction: in algorithms **H**, **GH** and **RH** the direction d^k is computed by direct methods (SVD or QR decomposition with column pivoting), whereas the algorithm **MH** proposes to approximate it in an iterative way, which is basically justified especially for large problems.

Later on, an optimized version of the algorithm **MH**, and the theoretical analysis of an unified approach to all four Han-type algorithm have been the subject of the paper [43]. Thus, the research team introduced the general form of a Han-Type algorithm, the algorithm **TH**, and give the necessary conditions that the direction d^k must satisfy in order that the algorithm **TH** to be classified as Han-type.

Many numerical experiments were performed with the four algorithms on two types of problems: linear separability problems and classical and maritime transportation problems, showing that the solutions computed by algorithm **MH** are reliable. The two types of constrained optimization problem are equivalent to systems of inequalities. If the optimization problems are inconsistent, the corresponding systems of inequalities will also be inconsistent, so we may solve them by algorithms **H, GH, RH** or **MH**. This study has been the subject of works [41], [45], [38] and [40].

In 2014, the research team, led by Contantin Popa, delivered [8], which was oriented to the numerical solution of (maritime) transportation problems, with emphasis on the unbalanced and inconsistent ones (i.e. when the set of classical feasible solutions is empty and we must consider the least squares ones). These kind of problems may appear in practice and the classical linear programming solution techniques, as e.g. Simplex-type algorithms, cannot handle the inconsistency difficulty. The authors show how one can equivalently transform an inconsistent linear programming problem into an inconsistent system of linear inequalities, which can be solved with Han - type algorithms they previously studied and proposed.

The most recent paper published by the research team, [37], introduces a comparative study how the between two approaches made to solve an unbalanced and inconsistent maritime transportation problem. One of them is by applying the **MH** algorithm, and the other one involves a soft computing technique that produces an original formulation of a genetic algorithm (GA) over a maritime transportation problem. The results proved to provide a cost optimized solution to some real world maritime transportation problems.

We restrict our presentation to the above results. The References contain all the papers published by Professor Popa. We leave to the interested reader the pleasure to study them. And to inspire new generation of scientists. This is Professor Popa's scientific legacy.

5. THOUGHTS OF FAMILY AND FRIENDS

We kindly asked several people that knew Professor Popa to remind briefly his warm personality in order for the reader to have a complete view on his character.

Family. *Doina Carp, wife:* " Writing or talking about Constantine is still difficult for me, because his passing away is so recent! We met at the Conference organized by him and held in Eforie Nord, in 1997. I appreciated the special attention he paid to each participant, the elegant way in which he coordinated the works and the calm, parental attitude in which he addressed the team of young colleagues that surrounded him. In 1998 I was elected vice-rector of Constanta Maritime University, during which time Constantine was the Director of the Department of Informatics at Ovidius University in Constanta. In these capacities, we worked together in organizing a Summer Camp of Informatics under the auspices of the Erlangen University (2005). The visit to our navigation simulator was highly appreciated by both participants and organizers. Our style of treating the assumed tasks with extreme seriousness had a strong impact on both of us, impressing each other. Then we grieved simultaneously at the loss of the mother in my case and the wife in his case, which allowed me to discover his great sensitivity, gentleness and kindness. He was an extremely charming person and a good listener. Step by step we became very close until we decided to unite our destinies. While the fatal moment of saying good bye for ever was approaching, I needed him to know that I was deeply feeling about our eight years together. I summed up in just a few words Every moment we spent together meant happiness to me! We also worked together which brought us even closer. He was a partner in the true sense of the word and in any circumstances. Constantine coordinated the team made up of Cristina Serban, he and I, in writing the book Algorithms for unbalanced maritime container transportation problem and also involved in publishing scientific papers. He distributed distinct, personalized, collaborative tasks that made the job seem easy. Constantine built partnerships that generated emulation and synergy among members, which eventually led to the development of so many scientific articles. He was extremely organized and liked to feel his days pleasant, to do useful things like sports, walking and reading. We went to symphonic concerts, to the theater and cinema, to the latest four editions of George Enescu Festival. We visited many beautiful places in this country, in Europe and the USA. He loved to travel, discover the world, visit museums and understand different cultures and ways of life! I must also remember his physical and moral beauty, his inability to do harm! Constantine was structurally and behaviorally a real gentleman! I consider myself fortunate and honored to have shared these eight years of my life with him!"

Andrii-Vlad, son: "My father (The Big Bear in our family) will always be a noble man, a responsible and deeply spiritual man, who was at the same time entirely dedicated to me and my mother (May her soul rest in peace!) and also very passionate of his work and career, sometimes up to totally neglecting sleep or any kind of well-deserved rest. He was and will always be a great father, who always wanted me to be realistic about any situation, and, to that, he would at all times support me emotionally (to the same extent as my mother) and give me a great hint about what could be done (he would always say he did not want to give me advice). My father helped me a lot (sometimes too much) and he has always been very patient (sometimes maybe too patient). I owe a lot to my father and I would like to thank him especially for all the times he had criticized me, it‘s been the right thing to build upon. As regards his communication with other people, my father was at all times gentle and perceptive, with a great sense of humor, but he always made sure, just like my mother, that his opinions and creeds were well understood. An iron hand in a velvet glove might suit him (and her) perfectly. There are certain things my father was strongly against, he has always been critical about injustice, sloppiness and different manifestations of stupidity but, at the same time, he was aware that some things might not be changed (by a few men and/or women), when all goes down to educational and/or cultural factors at different levels. He was also a man with a beautiful soul, maybe with the most open and genuine smile I've ever seen and who would laugh with all his heart. He was a strong and focused man, with a delicate soul and he was able to lend poetry and light to everything around him, he was able, for example, to see a blackbird or a butterfly in the middle of an illogically crowded street and focus on that blackbird or butterfly or the ridiculous portrait of a sea of gnarling spiritual pauperity and be rather moved by the prevailing pitiful ridiculousness of that picture. His unique personality will always be with us, here, anywhere, although I admit the misery of such a loss could only be expressed by, let‘s say, the tunes of Charlie Mingus, Johnny Cash, or the Doors (The End). May his soul rest in peace! "

Friends. *Gheorghe Juncu:* "I never thought I would have to write these words. Even now it is very difficult for me to accept the fact that Puiu is no longer among us. To me, Puiu represented a model of professionalism; a very intelligent and well-mannered person, but at the same time a very meticulous and rigorous one. His whole life was dedicated to these principles. Even when faced with a tragedy in his personal life, or with a promotion to a high administrative position which required considerable amount of additional work, Puiu did not abandon his high standards of professionalism."

Ulrich Ruede: "Constantin was a regular guest and visitor at my institutions for a period of almost 30 years. I remember meeting him at the main train station in Munich around 1990 and guiding him to TU Munich on his first visit. From then onwards, we remained in contact. Constantin came to visit in Munich and also when I moved to University of Augsburg in the mid 1990s. After I had moved to University of Erlangen in 1998, Constantin spent almost every year a few weeks visiting. In Erlangen, he also held a DAAD-financed visiting professorship for one year, teaching our Master students in numerical methods. In turn, Constantin had also invited me to visit Ovidius University in Constanta. Over the years, our scientific collaboration has followed our developing scientific interests, covering areas such as iterative algorithms, multigrid methods, ill-conditioned problems, regularization, and least squares problems. Often these methods were motivated by applications from engineering, as good work in applied mathematics often is. Constantins work has thus led to a sequence of joint articles. The most recent one will be appearing 2021 in the SIAM Journal of Scientitific Computing. Over these many years, Constantin and I have developed a close friendship, enjoying many evenings together with good food, a glass of wine or a beer, either in Erlangen or in Constanţa. We both felt privileged to live in a time when Europe had opened up and when travel, collaboration, and friendships like ours became possible. I have especially fond memories of our excursions. In Germany we jointly travelled in the Alps. In Romania in turn, Constantin showed me the beauty of the Black Sea coast. I will dearly miss Constantin, but these memories will remain."

Alexandru Morega: "Constantin Popa (Puiu) was a robust, tonic person, with a lot of entrepreneurial spirit and determination, around whom a professional creed can be built. How strange to talk about him in the past... His memory, the moments, and events lived together may mark a generation and an era of search and struggle to keep the "grand pavois" up and high in times of endless transition and rapid, uncertain change of values. But mathematics prevails, and Puiu dedicated himself to them. Until his last hour. We shall keep a bright and inspiring image that may help us go further."

Neculai Andrei: "Constantin Popa was a true Professor in every sense of the word on Numerical Computation and Applied Mathematics, with strong and interesting results in this field. He published plenty of papers and books, organized conferences and seminars, appreciated by the scientific community.

Alongside with his scientific research preoccupations, he was actively involved in the academic life of the Faculty of Mathematics at the Ovidius University in Constana, holding different managerial positions, loved and appreciated by both students and colleagues alike. Apart from his professional side, I highly regarded him for his honest character, sensitivity and great sense of humor. He was a reliable, close friend, always ready to give competent advice and help. My professional collaboration with him and also the holidays spent together will always be a nice memory. May his soul rest in peace, with God always watching over his eternal sleep."

Aurelian Nicola: "There are no words to describe the sorrow of losing a professor, mentor, colleague and friend. These few lines shortly describe my strong connection with him. I met professor Popa Constantin in my first year at the university while delivering the numerical analysis lectures. From the very beginning I was surprised the way he explained difficult mathematical things in an elegant manner, with calm and distinguished charm. As a student I was lucky to learn from the best professor. Since 1991, Constantin Popa guided me throughout my scientific career. I started as a teaching assistant for his lectures, Professor Popa having a lot of patience for my dull ignorance. After three years, he involved me in the process of writing a textbook. It has been a fantastic experience. I have working many hours with my mentor, feeling I was his colleague. I have graduated the first in class and I have applied for a position in the faculty. At this point, the mentor showed me the path by driven me to apply for a Master degree program at Weizmann Institute of Science, Israel. Afterwards, I have pursued a PhD program at University of Strathclyde, UK. After seven years, in 2005, I have rejoined the Mathematics and Computer Science Department to work along with Professor Popa. Since then, under the close supervision (as a mentor, colleague and best friend) he has driven me to publish several scientific papers in well established journals. I followed his footsteps one by one. I became Director of Department of Mathematics and Computer Science in 2016, and Dean of the Faculty in 2020. In all these 30 years I have understood that professor Popa was my friend in all the professional problems arisen in my life. Every time I had questions or need for advice, he was there for me. We have spent quality time together at several conferences. I wish to express my gratitude for the fact that I have met him. He has been like a second father to me."

Cristina Şerban: "I owe my professional success to wonderful scholars like prof. Popa. First, he delivered several lectures I had throughout the faculty and master studies; his positive attitude and in-depth explanations for difficult concepts greatly enriched every class he taught. Later on, he mentored my doctoral and postdoctoral thesis, providing advice and guidance and walking with me through every detail. Thus, prof. Popa played a great role in shaping my research development, taking me under his supervision, showing me how research is done, and how a researcher should think. For all the above, I am grateful and ever indebted to professor Constantin Popa."

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