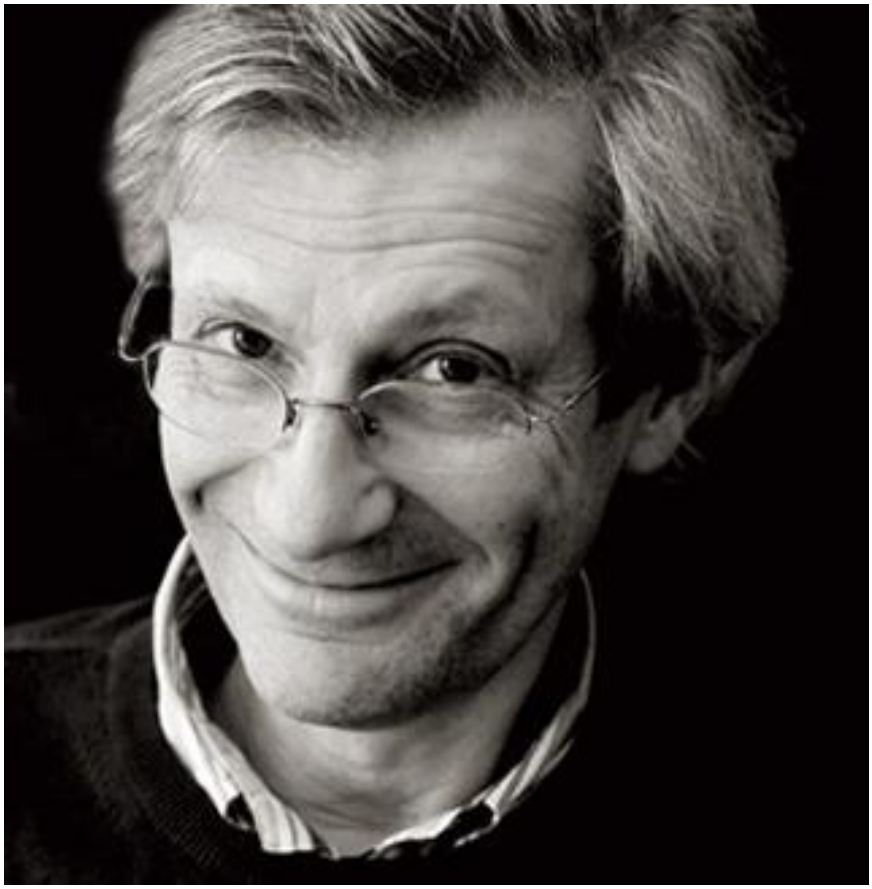
Happy Birthday

Paul Van Dooren



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Remembrances and wishes…

… from Bart De Moor

Dear Paul,



What can we say after almost 40 years of scientific collaboration and friendship? We can look back for one thing, much more of course than we can look forward. That is what we do in these messages from Joos, Sabine, Johan and me.

We can look at our scientific co-authorships, and that is why we include here all our co-publications of the last 40 years. A quick enumeration of the keywords testifies to your broad interests and intelligence: Smith-MacMillan form, Kalman filtering, SVD (updating, systolic arrays,…), generalizations of the SVD and the QR decomposition, subspace identification, software repositories like SLICOT, least squares support vector machines, … You shared your scientific expertise with many of us in Stadius at KU Leuven, as my colleagues will elaborate on in more detail below.

But even more importantly, what everybody for sure will remember is the commitment, the tact, the patience and the friendliness of your interactions with all of us. You stimulated interaction with all the many other people in your vast network (it is actually impossible to exhaustively enumerate all our common friends and colleagues).

Where did we learn to know each other? I don't remember. You graduated about 2 PhD life cycles before me, in 1979 (I in 1988), in Computer Science while I was in Electrical Engineering, both of us at KU Leuven. And of course, before we even met, I knew 'of you' as at that time your PhD, which culminated in the IEEE-AC publication "The generalized eigenstructure problem in linear system theory' was an immediate hit.

In a certain way, you are my scientific uncle, as my promotor, Joos Vandewalle, was also a PhD student of Patrick Dewilde, just like you. This makes Patrick your scientific father, and you my scientific uncle. From Patrick upwards, we share the same Mathematical Genealogy Tree (see https://www.genealogy.math.ndsu.nodak.edu for more details).

Where did we meet? Maybe you remember? Was it in Brussels while you worked at Philips, was it at some conference, or was it in Stanford? In any case, wherever I came, people kept on asking: 'Ah, you're from Leuven, do you know Paul Van Dooren?' And actually, for a couple of years, I did not, unless we met, somehow somewhere sometime, and the rest, as they say, is history.

Instead of describing all our adventures together, I will survey them in an after-dinner presentation, the slides of which are completely contained in this tribute bundle. There we will anecdotally treat your primary and secondary school years in Tienen at the Koninklijk Atheneum, your Leuven period, your uncountable presentations and visits and positions in other universities and at conferences, our co-publications, the many many interactions we had with and about our good friend and mentor, Gene Golub (whose father was from Ukraine!), who also studied at the

University of Illinois in Urbana-Champaign, where you were a professor once. He was, among many other things the main driving force for you to receive the James Wilkinson Prize in Scientific Computing.

By the way, who else can better describe and summarize your (scientific) life, than you yourself, for which I gladly refer to the interview you had with Younes Chahlaoui in 2011 (see https://eprints.maths.manchester.ac.uk/1674/1/PVDinterview-cor2.pdf).

I will tell the story of Gene's 15-th (sorry, 60-th) birthday party in Chicago, where I could not make it because Hilde was going to give birth to our oldest son. But as a birthday present, the community bought him a first cellular phone, on which I called him at the birthday party (after you called me to go on) to announce to him he would receive an honorary degree of KU Leuven. At that occasion, the Latin for SVD, 'valoribus decomponendis singularibus', was officially introduced (and since then the SVD is daily used in the Vatican's supercomputer).

Sadly, and happily at the same time, we co-organized the world-wide Golub Remembrance Day, on his birthday date, February 29th 2008, in Leuven (the event was handed over during 24 hours all over the world, in many places, among others, from Australia over China, Germany, Belgium, England to Stanford). At that occasion, I spoke about our joint work on Generalized SVD and QR decompositions. The Golub Remembrance Day was reported on in the local news, in the SIAM community and in several obituaries, including one in Nature.

Paul, of course, there are so many other things we could reminisce about, the times that Maggie and you and your kids visited us in Stanford and we traveled up north (the pictures of which are somewhere deeply buried in our immense but unsorted physical photo archives of 40 years ago), the many times we had lunch and dinner together, the Belgian IUAP network we were both proud and prominent members of, and so much more...

But I only selected the best memories, because those were the ones we had together in friendship.

What will the future bring ? Who knows? Obviously, staying in good health, both physically and mentally, is your main priority as of now, as it is ours. But for sure, as long as we remain active, we will certainly keep on meeting each other, and who knows, some more serious scientific work will emerge from that.

We wish you a healthy and happy future, to you, to Maggie, and to your whole family !

Your colleague, 'et ami quand même',

Leuven, July 2025,

Bart De Moor

… from Joos Vandewalle

Memories on the stimulating interactions with Paul Van Dooren over 51 years



Paul Van Dooren obtained his Master of Engineering in computer science in 1974, which is 3 years later than my graduation as electrical engineer. I had already started my PhD on digital design in electrical engineering immediately after graduating in 1971. The return to KU Leuven of Patrick Dewilde in 1972 with his enormous enthusiasm, and drive for system theory, made me switch subjects quickly from digital design to system theory. The stimulating discussion with Patrick soon led to several publications. So, when Paul also started in 1974 as the second PhD student with Patrick, I learned to know Paul and we met each other frequently most of the times with Patrick. I still remember several good discussions of the three of us as well as many casual and more philosophical discussions. Also, Patrick exposed Paul and me to several jewels of his research and interactions in California. The most crucial jewel that we received is the **Singular Value Decomposition.** It is an old mathematical theorem dating back to Beltrami 1873 and independently to Jordan 1874. It is more widely applicable than the eigenvalue decomposition, and that did typically not appear in the basic university linear algebra courses in the 1970ies and later. It has since been a key instrument in Stadius for research and linear algebra education in engineering. Paul was a quick learner with a keen interest in linear algebra and the numerical aspects of it, also looking for fundamental mathematical challenges. In 1974 I was already in the medium stage of my PhD that I finished in April 1976. Our thesis subjects were sufficiently different so that we did not have joint papers in that period, but we were using similar mathematical tools and references, and hence our discussions were mutually stimulating. While my thesis subject was related to multivariable linear system cascade decomposition by factorizing the matrix transfer function, Paul worked for his PhD thesis more towards singular pencils and the generalized eigenstructure. Soon after my PhD defense and marriage with Rita, both in the same month, we left Leuven for California in August 1976 for a three-year postdoc with Leon Chua on nonlinear circuits, at UC Berkeley. During this period, we kept some contact, but this was not so simple then, since internet and gsm did not exist. However out of our interactions came a joint publication.

Vandooren, P., Dewilde, P., Vandewalle, J. (1979). Determination of the Smith-macMillan form of a rational matrix from its Laurent expansion. IEEE Transactions on circuits and systems, 26 (3), 180-189.

During his PhD Paul had already strong international connections and made trips to visit the colleagues. So that was the start of his international mobility that he kept in his entire career and that is still not over now. So, in 1979 he finished his Ph.D at the Katholieke Universiteit Leuven 1979 entitled: *A generalized eigenstructure problem: applications in linear system theory* with advisors Patrick Dewilde who had moved to TUDelft then, and the late Ann Haegemans. After his PhD Paul moved for a postdoc period to California, and then I returned to Leuven, so that new cooperations did not come. Moreover, our research subjects were not so close anymore. I moved more towards circuits and system, digital design, cryptography, digital signal processing and systems and control.

With these topics I was able to attract excellent PhD students like Jan Staar, Bart De Moor, Sabine Van Huffel, and Yvo Desmedt from our own university and Tan Shao Hua, and Michel Verhaegen from outside. Michel Verhaegen was an aerospace engineering student from TU Delft who came to me for a PhD on algorithmic aspects of systems and control. During his PhD he interacted with Paul who was at that time at Philips Research Lab Brussels, and a nice publication was made.

Verhaegen, M., Vandewalle, J., Van Dooren, P. (1984). A robust and efficient technique for dealing with time-varying instrumental bias in linear filtering. IASTED Journal on Control and Computers, *12* (3).

Michel Verhaegen, a name that will come up later, finished his PhD in our group in1985. "*A new class of algorithms in linear system theory with application to real-time aircraft model identification".* He later made a nice career in TU Delft systems and control and kept good interactions with our group.

Later, a new PhD Marc Moonen started with me with a keen interest in signal processing linear algebra, algorithm design and telecommunication. During his PhD he already worked with Paul for several elements of his thesis that was finished in 1990: *Jacobi-Type Updating Algorithms for Signal Processing, Systems Identification and Control*

Here is the outcome of publications from that cooperation.

Moonen, M., Van Dooren, P., Vandewalle, J. (1991). Jacobi-type algorithms for ldu and cholesky factorization. Journal of parallel and distributed computing, 13 (1), 111-117.

Moonen, M., Van Dooren, P., Vandewalle, J. (1991). A note on efficient numerically stabilized rank-one eigenstructure updating. IEEE Transactions on signal processing, 39 (8), 1911-1913.

Moonen, M., Van Dooren, P., Vandewalle, J. (1993). A systolic array for svd updating. SIAM Journal on Matrix Analysis and Applications, 14 (2), 353-371.

Moonen, M., Van Dooren, P., Vandewalle, J. (1992). A singular value decomposition updating algorithm for subspace tracking. SIAM J. on Matrix Analysis and Applications, 13 (4), 1015-1038

Moonen, M., Van Dooren, P., Vandewalle, J. (1992). An SVD updating algorithm for subspace tracking. SIAM journal on matrix analysis and applications, (4), 1015-1038.

I was happy that another young PhD student of mine could benefit from interaction with Paul : Johan Suykens. One of his major masterpieces is the Least Squares Support Vector Machine, and it was given a boost by the contribution of Paul.

Suykens, J., Lukas, L., Van Dooren, P., De Moor, B., Vandewalle, J. (1999). Least squares support vector machine classifiers : a large scale algorithm. *Proc. of the European Conference on Circuit Theory and Design (ECCTD'99)*, (839-842).

Johan later developed a fantastic career in AI, SVM, data processing, and controller design.

After the closure of the Philips Research Lab Belgium, which was an excellent research center that could be compared to Bell Labs, Paul was hired by our sister university UCL. There he was very active until retirement/emeritate. During that period Paul Van Dooren and Vincent Blondel were the coordinators of a very successful DYSCO2 PAI national project, where we also were a partner.

On 9 November 2016 Paul became emeritus from UCL, and I was invited for a nice dinner celebration.

We did not really organize many joint workshops or conferences. However here is a very nice one that I would like to mention:

Numerical Linear Algebra, Digital Signal Processing and Parallel Algorithms. NATO Advanced Study Institute held in Leuven, August 1–12, 1988 Organizers :T Kailath, F Luk, J McWhirter, D Sorensen, J Vandewalle, Danny Sorensen, Paul Van Dooren

How can I characterize Paul in a few keywords: Intelligence, mobility, adaptability, intellectual strength, perseverance, focused communications and constructive interventions.

Some more personal interactions.

- The father of my daughter in law, Arthur Vranckx happens to be the best school friend of Paul. They both attended the same high school in Tienen for 6 years and took the strong mathematics tracks. During the early years of high school both were the two smallest of the class, and this also brought them together. Things have changed and now Paul is far from being in the community of small people. They were often sitting next to each other in class, and their scores for math were both very high. Apparently during these high school years, the fire for mathematics was ignited in the two and would not extinguish. Arthur Vranckx became Master in Mathematics and, as his father he, was teaching mathematics in the same school in Tienen. Paul took a different track with computer engineering, but the mathematics is playing a very important role and he does not stop with it, and moreover Paul could be spotted worldwide.

- Paul is spending since his retirement often long periods in abroad Madrid, Helsinki, Berlin and so on. I happen to come yearly for the past ten years for a couple of days for an award jury deliberation to Madrid. So at one of these occasions, we were both together in February and Paul and I had a nice dinner together. I must say that he knows the good restaurants and the good Spanish dishes.

- Since a few years the four of us Paul, Patrick, Michel Verhaegen and myself and our wives Maggy, Anne, Hilde and Rita try to have a yearly meeting rotating at our homes. Moreover, the wives also have some joint activities.

- Maggy and Paul were invited at the exhibition of my sculptures in my garden in September 2023. Since Paul was abroad then, Maggy came alone and transmitted to Paul the pictures and information sheets of the sculptures. Quickly thereafter Paul sent me a nice email with compliments on my sculptures. Apparently, Paul considers the sculptures very typical for me. Well, Paul and Maggy this year on 20 and 21 of September there is another occasion to come and see my sculptures in 3D, if you are not abroad of course.

What can we wish for the future ?

Do what you like to do, so long as you can and while you sense the fire for intriguing mathematical problems.

… from Sabine Van Huffel

Dear Paul,



First of all, congratulations on your 75th birthday. Unfortunately, I could not attend this unique workshop dedicated to your birthday and the impact your research had on the research community, in particular the field of numerical linear algebra and systems and control theory.

We got to know each other in 1983 when I was only a few weeks a PhD student under the supervision of Joos Vandewalle. You were then working as a researcher in Philips Research Laboratory in Watermaal-Bosvoorde. Joos asked me to join the Benelux Working Group on Software (WGS) which met regularly in the main building of Eindhoven University of Technology with the aim of developing a numerically reliable software library in Fortran 77 for system and control theory. Jan Staar's PhD included a wealth of such routines. Since I was doing a PhD on one of the unfinished chapters of his thesis and had followed the numerical analysis track in my master's degree in computer science, I was the perfect person for this. For my first meeting, you were supposed to pick me up at the viaduct in Heverlee. But you didn't show up! It turned out afterwards that you had mistaken the time and left an hour earlier. So I missed my first appointment at WGS. But this was compensated afterwards. Together with Ruth Kool, Aloys Geurts, Ad van den Boom, you and I and later Sven Hammarling from NAG in Oxford, UK, we built out the standards for the software and developed the first software library, SYCOT, later called SLICOT (Subroutine Library in Control Theory). I remember very well the anecdote where our first tape was sent from the Netherlands to Belgium marked ‘tape with software’ and got stuck at customs. What happened? Customs had received the tape but were still waiting for the software! Soon after, Andras Varga from DLR (see PHOTO 1) and Volker Volker Mehrmann from TU Berlin also joined our group. High time to get European.

Since you moved to the University of Illinois at Urbana-Champaign for a few years to pursue an academic career, I had become president of WGS in the meantime. We applied for European funding to build a network, entitled NICONET (Numerics in Control Network), to further develop our numerically reliable Fortran 77 software library. Vasile Sima was recruited and became the perfect expert to maintain, extend, test,… our software library. The group was expanded with Bo Kagström, Peter Benner, Heike Fassbender, Petko Petkov, and others (too many to mention). NICONET first became a Belgian non-profit organization, then a German one under the chairmanship of Peter Benner. The SLICOT library was considerably expanded with several modules from the field of system and control theory. A real breakthrough came when we embedded the numerically robust and computationally efficient SLICOT routines as an underlay in Matlab toolboxes. All the software was publicly available. Moreover, we were able to sell the entire SLICOT library to Mathworks in two stages. We didn't get rich from it, but it was enough to continue paying Vasile Sima to maintain the library. On March 23 in 2017, we met again with the original WGS group at TU Eindhoven and Maggie was with us. In 2023, we discontinued the NICONET society. This was my longest and most intense collaboration with you throughout my career: we worked together during 40 years on the expansion of SLICOT and NICONET in an ever-

expanding network. Our joint papers largely describe our efforts. I look back with great gratitude on these years of cooperation, which also became more friendly as the years went by.

I also collaborated with you in other projects, including my PhD research on the total least squares approximation. I had just invented a formidable new algorithm after several weeks of research. Joos and I were preparing a first publication when you came in and told us that you had already seen this algorithm in a paper by Gene Golub and Charlie Van Loan. You can imagine how disappointed I was at the time! Yet there were small differences that I continued to work on and discovered new properties and algorithms as a result. You also put us in touch with Gene Golub who was so enthusiastic about my work and the new applications I was working on. Gene believed in me, my abilities, my research... and made me rise above myself. Thanks to Gene, I was able to organize 4 highly interdisciplinary workshops in Leuven around Total Least Squares between 1991 and 2006. As a member of the programme committee of these workshops and as assessor of my PhD, you were always closely involved in my research, and I could always turn to you for advice. We met at many conferences and workshops such as the Householder symposia, the SIAM meetings on linear algebra, MTNS, but also at Benelux meetings in Systems and Control.

Nicola Mastronardi's doctoral work and his postdoctoral research with Marc Van Barel from the computer science department's NALAG group also brought us all closer together again. Thanks to Nicola's semi-annual visits to KU Leuven and UC Louvain, we stayed in touch. In late August 2023, we were able to celebrate Marc Van Barel's retirement together in the same place as today with an interesting workshop (see PHOTO 2). I retain fond memories of this togetherness and the trips I did in the area together with my husband Johan.

Meanwhile, I have been emerita since 1 October 2020 (in corona pandemics time) and have gradually handed over my research to my successor to pursue new avenues: I am a proud grandmother of 5 grandsons, and I am increasingly engaged in climate action. If we want to give a future to our grandchildren and leave behind a cleaner planet, a switch to a sustainable system is more than urgent at this time of climate change, biodiversity loss and increasing inequality. Current systems are bumping up against their limits. We are looking for solutions in sectors where transition is most needed such as mobility, energy, food, economy and construction. Systems and control theory will not save us. A huge shift in consciousness is needed for this: from ego to eco. We continue to hope and believe that every step towards climate transition brings us closer to this future dream.

Paul, you keep on searching and discovering new algorithms, it's fulfilling, and you find pleasure in it! As long as you feel those jitters, I say go ahead, it's your life! You remain a formidable inspirator and enthusiastic supervisor. Enjoy many more years, together with Maggie!

Many thanks for many years of friendship,



Prof. Em. Dr. Ir. Sabine Van Huffel

p.s. Quote from Andras Varga: "*Attached is a photo from the early days of my involvement in WGS (I think taken in 1992 at a WGS meeting at NAG in Oxford). Ruth was in many ways a central person in WGS, as is also highlighted by this photo. He was always very polite and helpful in every way. Strangely, until our first meeting in 1991, I was convinced that he was a ... woman*". The picture shows from left to right: Andras Varga, Aloys Geurts, Ruth Kool, Sabine Van Huffel and Ad van den Boom. Paul was not there at the time because he was then working at the University of Illinois at Urbana-Champaign.



Photo taken in late August 2023 at Marc Van Barel's retirement celebration at the Hotel Sierra Silvana in Selva di Fasano. From left to right: Teresa Laudadio, Maria (wife of Marc), Nicola Mastronardi, Marc Van Barel, Paul, Raf Van den Bril. In the background Antonio (son of Teresa and Nicola).



... from Johan Suykens (in Dutch)

Beste Paul,

Van harte proficiat met uw 75ste verjaardag! Time flies ...



Het was altijd fantastisch om een super-expert van matrices zoals u te kennen en op u beroep te mogen doen. Bij iedere vraag begon je onmiddellijk te goochelen met de wiskundige formules met operaties op matrices tot het gewenste resultaat eruit rolde.

Over de jaren heen had het talrijke toepassingen rond SVD, grafen, netwerken, optimalisatie, kernel methoden, machine learning en zoveel meer.

Hierbij een greep uit onze vroegere samenwerkingen met o.a. de "Van Dooren trick" om LS-SVM stelsels met conjugate gradient te kunnen lossen en om te zetten tot een positief definiete matrix, het opleggen van stabiliteit en positive realness bij het identificeren van lineaire toestandsruimte modellen en stochastische processen via regularizatie:

99-14

Suykens J.A.K., Lukas L., Van Dooren P., De Moor B., Vandewalle J., ``Least squares support vector machine classifiers : a large scale algorithm'', in *Proc. of the European Conference on Circuit Theory and Design (ECCTD'99)*, Stresa, Italy, Sep. 1999, pp. 839-842.
Lirias number: 1690552.

99-81

Van Gestel T., Suykens J.A.K., Van Dooren P., De Moor B., ``Identification of stable models in subspace identification by using regularization'', *IEEE Transactions on Automatic Control*, vol. 46, no. 9, Sep. 2001, pp. 1416-1420.
Lirias number: 636657.

00-30

Van Gestel T., Suykens J.A.K., Van Dooren P., De Moor B., ``Imposing stability in subspace identification by regularization'', in *Proc. of the 39th IEEE Conference on Decision and Control (CDC2000)*, Sydney, Australia, Dec. 2000, pp. 1555-1560.
Lirias number: 636654.

02-104

Goethals I., Van Gestel T., Suykens J.A.K., Van Dooren P., De Moor B., ``Identification of Positive Real Models in Subspace Identification by using Regularization'', *IEEE Transactions on Automatic Control*, vol. 48, no. 10, Oct. 2003, pp. 1843-1847.
Lirias number: 636464.

02-204

Goethals I., Van Gestel T., Suykens J.A.K., Van Dooren P., De Moor B., ``Identifying positive real models in subspace identification by using regularization'', in *Proc. of the 13th System Identification Symposium (SYSID2003)*, Rotterdam, Nederland, Aug. 2003, pp. 1411-1416.
Lirias number: 1691115.

Heel veel dank voor al deze mooie samenwerkingen en uw uitzonderlijke expertise! Nog vele mooie jaren.

Johan Suykens

Co-Publications

International Journal Papers

79-01

Van Dooren P., Dewilde P., Vandewalle J., ``On the determination of a Smith-MacMillan form of a rational matrix from its Laurent expansion'', *IEEE Trans. on Circuits and Systems*, vol. 26, no. 3, 1979, pp. 180-189.

84-01

Verhaegen M., Vandewalle J., **Van Dooren** P., ``A robust and efficient technique for dealing with time-varying instrumental bias in linear filtering'', *IASTED Journal on Control and Computers*, vol.12, no.3, 1984.

89-13

Moonen M., **Van Dooren** P., Vandewalle J., ``An SVD updating algorithm for subspace tracking'', SIAM J. Matrix Anal. Appl. vol.13, no.4, Oct. 1992, pp. 1015-1038.

89-13a

Moonen M., **Van Dooren** P., Vandewalle J., ``A systolic array for SVD updating'', SIAM J. Matrix Anal. Appl., vol.14 (1993), no.2, Apr. 1993, pp. 353-371.

89-23a

Moonen M., **Van Dooren P.**, Vandewalle J., ``A systolic algorithm for QSVD updating'', Signal Processing, vol.25, no.2, 1991, pp. 203-213180

.

90-20

Moonen M., **Van Dooren P.**, Vandewalle J., ``A Note on 'Efficient Numerically Stabilized Rank-One Eigenstructure Updating'"', *IEEE Transactions on Signal Processing*, vol.39, no.8, Aug. 1991, pp. 1911-1914.

90-21

Moonen M., **Van Dooren** P., Vandewalle J., ``Jacobi-type algorithms for LDU and Cholesky factorization'', J. of Parallel and Distributed Computing, Vol 13, 1991, pp. 111-117.

91-03

De Moor B., **Van Dooren** P., ``Generalizations of the QR and the singular value decomposition'', *SIAM Journal on Matrix Analysis and Applications*, vol.13, no.4, Oct. 1992, pp. 993-1014.

92-31

Moonen M., **Van Dooren** P., Vanpoucke F., ``On the QR algorithm and updating the SVD and URV decomposition in parallel'', *Linear Algebra and its Applications*, vol.188, 1993, pp. 549-568.

92-33

De Moor B., ``Structured total least squares and L_2 approximation problems'', *Systems & Control*, Special Issue of Linear Algebra and its Applications on Numerical Linear Algebra, (**Van Dooren**, Ammar, Nichols, and Mehrmann, eds.), vol.188-189, Jul. 1993, pp. 163-207 (also IMA Preprint Series no.1036, Institute for Mathematics and its Applications, University of Minnesota, Sep. 1992).

99-81

Van Gestel T., Suykens J.A.K., **Van Dooren P.**, De Moor B., ``Identification of stable models in subspace identification by using regularization'', *IEEE Transactions on Automatic Control*, vol. 46, no. 9, Sep. 2001, pp. 1416-1420.

99-82

Mastronardi N., Van Dooren P., Van Huffel S., ``On the stability of the generalized Schur algorithm'', *Lecture notes in Computer Science*, vol. 1988, 2001, pp. 560-567.

00-08

Mastronardi N., Kressner D., Sima V., **Van Dooren P.**, Van Huffel S., ``A fast algorithm for subspace state-space system identification via exploitation of the displacement structure'', *Journal of Computational and Applied Mathematics*, vol. 132, no. 1, 2001, pp. 71-81.

02-104

Goethals I., Van Gestel T., Suykens J.A.K., **Van Dooren P.**, De Moor B., ``Identification of Positive Real Models in Subspace Identification by using Regularization'', *IEEE Transactions on Automatic Control*, vol. 48, no. 10, Oct. 2003, pp. 1843-1847.

07-234

Mastronardi N., Golub G.G., Chandrasekaran S., Moonen M., **Van Dooren P.**, Van Huffel S., ``Numerical Linear Algebra in Signal Processing Applications'', *EURASIP Journal on Advances in Signal Processing*, editorial, vol. 2007, 2007, pp. 1-3.

International Conference Papers

89-38

Moonen M., **Van Dooren P.**, Vandewalle J., ``Updating Singular Value Decompositions. A parallel implementation'', in In *Advanced Algorithms and Architectures for Signal Processing IV*, Proc. SPIE conference, San Diego, 1989, pp. 1152-1158.

90-33

Moonen M., **Van Dooren P.**, Vandewalle J., ``Combined Jacobi- type Algorithms in Signal Processing'', in In SVD and Signal Processing, II: Algorithms, Analysis and Applications, R. Vaccaro, ed., Elsevier Science Publishers B.V. (North-Holland), 1991, pp. 177-188.

90-42

Moonen M., **Van Dooren P.**, Vandewalle J., ``SVD updating for tracking slowly time-varying systems. A parallel implementation'', in *Proc. of the Mathematical Theory of Networks and Systems Symposium (MTNS'89); Signal Processing, Scattering and Operator Theory, and Numerical Methods*, (Kaashoek M.A., Van Schuppen J.H., and Ran A.C.M., eds.), Birkhäuser, 1990, pp. 487-494.

91-43

Van Huffel S., ``The generalized total least squares problem: formulation, algorithm and properties'', in *Numerical Linear Algebra, Digital Signal Processing and Parallel Algorithms*, (Golub G., **Van Dooren** P., eds.), NATO ASI Series, vol.F70, Springer-Verlag, Berlin, Germany, 1990, pp. 651-660.

91-44

Van Den Boom A., Brown A., Dumortier F., Geurts A., Hammarling S., Kool R., Vanbegin M., **Van Dooren P.**, Van Huffel S., ``SLICOT, a subroutine library in control and systems theory'', in *Proc. of the 5th IFAC Symposium on Computer Aided Design in Control Systems*, Swansea, UK, Jul. 1991, pp. 89-94.

99-14

Suykens J.A.K., Lukas L., **Van Dooren** P., De Moor B., Vandewalle J., ``Least squares support vector machine classifiers : a large scale algorithm'', in *Proc. of*

the European Conference on Circuit Theory and Design (ECCTD'99), Stresa, Italy, Sep. 1999, pp. 839-842.

00-30

Van Gestel T., Suykens J.A.K., **Van Dooren** P., De Moor B., ``Imposing stability in subspace identification by regularization'', in *Proc. of the 39th IEEE Conference on Decision and Control (CDC2000)*, Sydney, Australia, Dec. 2000, pp. 1555-1560.

00-84

Mastronardi N., Van Dooren P., Van Huffel S., ``Fast implementation of the QR factorization in subspace identification'', in *Proc. of the UKACC International Conference Control 2000 (UKACC)*, Cambridge, United Kingdom, Sep. 4-7, 2000, 6 p.

02-204

Goethals I., Van Gestel T., Suykens J.A.K., Van Dooren P., De Moor B., ``Identifying positive real models in subspace identification by using regularization'', in *Proc. of the 13th System Identification Symposium (SYSID2003)*, Rotterdam, Nederland, Aug. 2003, pp. 1411-1416.

04-150

De Moor B., Motmans B., Willems J., Van Dooren P., Blondel V., *Mathematical Theory of Networks and Systems*, Proceedings of Sixteenth Internatinal Symposium on Mathematical Theory of Networks and Systems, K.U.Leuven (Leuven, Belgium), (ISBN 90-5682-517-8), 2004, 1 p.

PhD thesis

01-44

Mastronardi N., *Fast and reliable algorithms for structured total least squares and related matrix*, PhD thesis, Faculty of Engineering, KU Leuven (Leuven, Belgium), K.U.Leuven, May 2001, 159 p.
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First pages.... but not the last ones...

79-01

On the Determination of the Smith–Macmillan Form of a Rational Matrix From Its Laurent Expansion

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***Abstract*—A novel method is presented to determine the Smith–Macmillan form of a rational $m \times n$ matrix $R(p)$ from Laurent expansions in its poles and zeros. Based on that method, a numerically stable algorithm is deduced, which uses only a minimal number of terms of the Laurent expansion, hence providing a shortcut with respect to cumbersome and unstable procedures based on elementary transformations with unimodular matrices.**

The method can be viewed as a generalization of Kublanovkaya's algorithm for the complete solution of the eigenstructure problem for $\lambda I - A$. From a system's point of view it provides a handy and numerically stable way to determine the degree of a zero of a transfer function and unifies a number of results from multivariable realization and invertibility theory. The paper presents a systematic treatment of the relation between the eigen-information of a transfer function and the information contained in partial fraction or Laurent expansions. Although a number of results are known, they are presented in a systematic way which considerably simplifies the total picture and introduces in a natural way a number of novel techniques.

I. Introduction

THE PROBLEM of efficient determination of the Smith–Macmillan form of a rational $m \times n$ matrix $R(p)$ does not seem to have received a great deal of attention in the past, although its importance as a key element in systems analysis and design can hardly be denied. The classical method of using unimodular matrix manipulations is cumbersome and not suited for numerical computations, because it results in an extraordinarily large number of polynomial manipulations. In all methods based hereon, numerical stability is lost because pivoting is not based on the coefficients of p but on its power [1].

On the other hand, a number of papers are devoted to the realization problem for system transfer functions and a host of algorithms have been devised [2]–[7]. Another set of algorithms were proposed for system inversion both in the case of systems over a finite field [8]–[10] and in the case of systems over $\mathbb{C}$ or $\mathbb{R}$ [11], and criteria for system invertibility where derived [12], [13]. Most of these methods require the handling of large size matrices and none devote any attention to the numerical stability problem.

An answer to the invertibility problem is needed, e.g., in coding theory where one is interested in deciding whether the transfer function has a unique zero at infinity (of large degree) and if so, in determining the degree of that zero and the inverse of the matrix. Also, in invertibility theory one wishes to know whether there is actually a zero at infinity in which case the system cannot be inverted. In

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A ROBUST AND EFFICIENT TECHNIQUE FOR DEALING WITH TIME-VARYING INSTRUMENTAL BIAS IN LINEAR FILTERING

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Indexing terms: Linear Filtering, zero bias errors, controllability

Abstract

A unifying approach is formulated for estimating zero bias errors on input signals of linear discrete dynamic systems in real time applications.
Generally, these parameters are treated by extending the state vector, hence introducing eigenvalues on the unit circle and uncontrollable modes. These two effects cause convergence difficulties of the Riccati Equation (RE). In the paper, a technique has been developed to make the system naively controllable with minimal system modification. Hereby, 'good' convergence behaviour of the RE is assured and linear forgetting is established automatically for the bias parameters. This allows to deal with constant or slowly time-varying zero bias errors.
Furthermore, a new implementation of the 'square root covariance filter' algorithm is described. It uses 'condensed forms' (Hessenberg or Schur) of the system structure and exploits the modelling of the bias terms. This leads to substantial savings in computing time compared to the conventional Kalman Filter implementation, with numerical superiority.
The resulting technique is demonstrated by simulation on the flight-path reconstruction problem that occurs in a two-step identification method. Here the system model is inherently 'condensed'.

1. Introduction

The system model used in INS (Inertial Navigation Systems) or in the flight-path reconstruction problem of a two-step aircraft model identification method is accurately known. For a given stationairy flight reference condition the model is linear, time-invariant with known system matrices [1,2]. This mathematical system description is ideally suited for Kalman-Bucy recursive filter techniques [3] to reconstruct the aircraft's flight path (or the state of the system). In practical applications, it is well known that the filter estimates are only useful over a restricted period of time, depending on the accuracy of the inertial measurement system used. One of the main reasons is the presence of accelerometer zero bias errors and gyro drifts. To reduce the estimation errors caused by these parameters ,it is a common practice to extend the state of the original system with the bias errors, assuming the latter parameters are constant. In this case, the filter will estimate both the states of the original system and the bias terms.
Until now, a lot of effort is spent in the development of efficient computational techniques [4] to solve the extended filtering problem. These techniques are based on the generalized partitioning estimation method of Lainiotis [5], to separate the estimation of the state variables from the bias terms.
However, the influence of this modelling on the numerical behaviour of the discrete RE is not yet discussed. But simulations studies have already shown that it may lead to severe deterioration of the estimation results, especially in real-time applications.

In this paper, the influence of extending the state vector by the input zero bias errors on the convergence of the RE as well as on the accuracy of the estimation results will be analyzed.
In section 2, the problem of extending the state description to include the zero bias errors on the input signals is formulated. Also the special features of the mathematical model used in the simulation to reconstruct the aircraft's flight-path are discussed in this section. The method to make the corresponding modes of the zero bias terms controllable is given in section 3, as well as the effect on the convergence of the Riccati Recursion (RR). An efficient implementation of the results of section 3 in a more reliable Square Root Covariance Filter (SRCF) will be given in section 4. In section 5, we will demonstrate the good performance of the derived algorithm in the case of simulated constant and linear time-varying bias errors. Section 6, presents the conclusions of this analysis.

2. The extended state space description

Let us consider the following discrete time-invariant system, that also appears in the flight-path reconstruction model [1,2]:

$$\text{process:}\quad x_{k+1} = A\,x_k + F\,w_k + B\,[w_k + b_k] \qquad (1)$$

$$\text{observation:}\quad y_k = C\,x_k \qquad (2)$$

where $x_k \in R^n$, $w_k \in R^m$ and $v_k \in R^p$. The deterministic input signal is given by u_k. The sequence w_k and v_k are Gaussian uncorrelated white noise with zero mean and covariances Q_k and R_k, respectively. The input is contaminated with bias errors b_k ^{m} assumed to be constant, i.e.

$$b_{k+1} = b_k \qquad (3)$$

The inclusion of these bias errors in an extended state vector, gives rise to the following model:

$$\begin{pmatrix} b \\ x \end{pmatrix}_{k+1} = \begin{bmatrix} I_m & 0 \\ B & A \end{bmatrix} \begin{pmatrix} b \\ x \end{pmatrix}_k + \begin{pmatrix} 0 \\ B \end{pmatrix} w_k \qquad (4)$$

$$y = \begin{bmatrix} 0 & C \end{bmatrix} \begin{pmatrix} b \\ x \end{pmatrix}_k + v_k \qquad (5)$$

or,

$$x_e(k+1) = A_e\,x_e(k) + B_e\,w_k \qquad (6)$$

$$y_k = C_e\,x_e(k) \qquad (7)$$

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A SINGULAR VALUE DECOMPOSITION UPDATING ALGORITHM FOR SUBSPACE TRACKING*

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Abstract. In this paper, the well-known QR updating scheme is extended to a similar but more versatile and generally applicable scheme for updating the singular value decomposition (SVD). This is done by supplementing the QR updating with a Jacobi-type SVD procedure, where apparently only a few SVD steps after each QR update suffice in order to restore an acceptable approximation for the SVD. This then results in a reduced computational cost, comparable to the cost for merely QR updating.

The usefulness of such an approximate updating scheme when applied to subspace tracking is examined. It is shown how an $\mathcal{O}(n^2)$ SVD updating algorithm can restore an acceptable approximation at every stage, with a fairly small tracking error of approximately the time variation in $\mathcal{O}(n)$ time steps.

Finally, an error analysis is performed, proving that the algorithm is stable, when supplemented with a Jacobi-type reorthogonalization procedure, which can easily be incorporated into the updating scheme.

Key words. singular value decomposition, recursive algorithms

AMS(MOS) subject classifications. 65F15, 65F25

C.R. classification. G.1.3

1. Introduction.

In many signal processing applications, it is necessary to continuously update matrix decompositions as new measurement vectors are appended as additional rows. Such problems frequently occur in beam forming, direction finding, spectral analysis, etc. [21]. Efficient updating techniques have long been known for the QR decomposition [8], while the more difficult problem of updating the (ordinary) singular value decomposition (SVD) has only recently been addressed [1], [2], [4], [9], [20].

Previously described techniques for row updating of the SVD mostly reduce to computing the rank-one modification of the corresponding symmetric eigenvalue problem [1], [2], [9]. A major drawback is the necessary knowledge of the exact eigenstructure of the original matrix in order to compute the updated eigenstructure. For real-time applications, where in each time step an exact updating is thus to be performed, this results in an unacceptably heavy computational load, viz., $\mathcal{O}(n^3)$ per update. Moreover, round-off errors due to the use of finite precision arithmetic are likely to accumulate unboundedly.

In this paper, we derive a fast SVD updating technique as a combination of QR updating on the one hand and a Jacobi-type SVD procedure on the other hand. The updating scheme provides only an approximate decomposition after each update. It has a low computational complexity—$\mathcal{O}(n^2)$ per update and it is particularly suited to parallel implementation [18].

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003

A SYSTOLIC ARRAY FOR SVD UPDATING*

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Abstract. In an earlier paper, an approximate SVD updating scheme has been derived as an interlacing of a QR updating on the one hand and a Jacobi-type SVD procedure on the other hand, possibly supplemented with a certain re-orthogonalization scheme. This paper maps this updating algorithm onto a systolic array with $O(n^2)$ parallelism for $O(n^2)$ complexity, resulting in an $O(n^0)$ throughput. Furthermore, it is shown how a square root-free implementation is obtained by combining modified Givens rotations with approximate SVD schemes.

Key words. singular value decomposition, parallel algorithms, recursive least squares

AMS(MOS) subject classifications. 65F15, 65F25

CR classification. G.1.3

1. Introduction. The problem of continuously updating matrix decompositions as new rows are appended frequently occurs in signal processing applications. Typical examples are adaptive beamforming, direction finding, spectral analysis, pattern recognition, etc. [13].

In [12], it has been shown how an *SVD updating* algorithm can be derived by combining QR updating with a Jacobi-type SVD procedure applied to the triangular factor. In each time step an *approximate decomposition* is computed from a previous approximation at a *low computational cost*, namely, $O(n^2)$ operations. This algorithm was shown to be particularly suited for *subspace tracking* problems. The tracking error at each time step is then found to be bounded by the time variation in $O(n)$ time steps, which is sufficiently small for applications with slowly time-varying systems. Furthermore, the updating procedure was proved to be *stable* when supplemented with a certain re-orthogonalization scheme, which is elegantly combined with the updating.

In this paper, we show how this updating algorithm can be mapped onto a *systolic array* with $O(n^2)$ parallelism, resulting in an $O(n^0)$ throughput (similar to the case for mere QR updating; see [5]). Furthermore, it is shown how a square root-free implementation is obtained by combining modified Givens rotations with approximate SVD schemes.

In §2, the updating algorithm is briefly reviewed. A systolic implementation is described in §3 for the easy case, where corrective re-orthogonalizations are left out. In §4, it is shown how to incorporate these re-orthogonalizations. Finally, a square root-free implementation is derived in §5.

2. SVD updating. The *singular value decomposition* (SVD) of a real matrix $A_{m\times n}$ $(m \geq n)$ is a factorization of A into a product of three matrices

$$A_{m\times n} = U_{m\times n} \cdot \Sigma_{n\times n} \cdot V^T_{n\times n},$$

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A systolic algorithm for QSVD updating

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Abstract. In earlier reports, a Jacobi-type algorithm for SVD updating has been developed and implemented on a systolic array. Here, this is extended to a generalized decomposition for a matrix pair, viz. the quotient singular value decomposition (QSVD). Updating problems are considered where new rows are appended to either one or both of the matrices involved. Systolic arrays as well as square root free implementations are described.

Zusammenfassung. In vorausgehenden Berichten wurde ein Jacobi-ähnlicher Algorithmus zur fortlaufenden Aktualisierung der SVD einer Matrix und die zugehörige Realisierung auf einem systolischen Array vorgestellt. In diesem Beitrag wird eine Erweiterung auf die verallgemeinerte Zerlegung eines Matrizenpaares, die sogenannten Quotient SVD (QSVD), behandelt. Es werden Aufgabenstellungen betrachtet, bei denen entweder nur eine oder beide beteiligten Matrizen durch Hinzunahme neuer Zeilen aktualisiert werden. Außerdem werden wurzelfreie Realisierungen sowie systolische Arrays beschrieben.

Résumé. Un algorithme de type Jacobi pour la mise à jour de la décomposition en valeurs singulières (SVD) a été développé et implanté sur un réseau systolique dans des articles antérieurs. Nous l'étendons ici à la décomposition généralisée pour une paire de matrices, c'est à dire pour la décomposition en valeurs singulières quotient (QSVD). Nous considérons les problèmes de mise à jour impliqués par l'ajout de nouvelles lignes à une ou aux deux matrices considérées. Nous décrivons des implantations sur réseau systolique et des implantations sans calcul de racine carrée.

Keywords. Singular value decomposition, parallel algorithms, recursive algorithms.

1. Introduction

The problem of continuously updating matrix decompositions as new rows are appended, frequently occurs in signal processing applications such as adaptive beamforming, direction finding and spectral analysis. An efficient technique for updating the singular value decomposition (SVD), amenable to systolic implementation, has been developed in [10, 11]. In the present paper, this approach is extended to a generalized decomposition for a matrix pair, viz. the quotient singular value decomposition (QSVD).[1] We consider updating problems where new rows are appended to either one or both of the matrices involved. As far as we know, these problems had not been looked at so far.

The approach to SVD updating consists in combining QR-updating with a Jacobi-type algorithm for the SVD, applied to the triangular factor. In each step, only $O\{n^2\}$ operations are performed,

[1] Formerly known as generalized singular value decomposition. See [1] for a standardized nomenclature.

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TABLE II
COMPARATIVE PERFORMANCE BETWEEN THE ALTERNATING PROJECTION METHOD AND THE NEW PROPOSED ENHANCED SPATIAL SMOOTHING FOR THE SOURCE AT 5° AND BASED ON 100 INDEPENDENT TRIALS

	RMS Error		
	Number of Snapshots		
Method	50	100	500
Alternating projection	1.9	1.7	0.57
Paper's method	0.0223	0.0153	0.0065

fully coherent sources at $-1°$ and $5°$ in our simulation. The rms errors of the DOA estimate of the source at $5°$, for different numbers of snapshots, are compared with those obtained from [8] in Table II.

From these results, it is clear that the signal enhancement method proposed here along with the spatial smoothing can significantly improve the resolution of the eigenspectrum for coherent signals.

V. Conclusion

In this correspondence, a new method for enhancement of the signal is proposed which is devised only for coherent signals. The proposed method along with the conventional spatial smoothing is used for estimation of the DOA's of coherent sources. Statistical behavior of the proposed approach, via the Monte Carlo method, demonstrate the significant improvement in the mean-square error and the resolution of the eigenspectrum.

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A Note on "Efficient Numerically Stabilized Rank-One Eigenstructure Updating"

Marc Moonen, Paul Van Dooren, and Joos Vandewalle

***Abstract*—In a recent paper, DeGroat and Roberts developed a reorthogonalization scheme for stabilizing eigenstructure updating algorithms. In this correspondence, we show that only part of this scheme, namely the renormalization, is essential for the stability, so that a cheaper scheme, with roughly half as many computations, can perform equally well.**

Introduction

Many present-day signal processing algorithms involve a rank-one updating of an eigenvalue decomposition (EVD). In most cases, an estimated data covariance matrix R is updated after each sampling

$$R_k = \alpha \cdot R_{k-1} + (1 - \alpha) \cdot x_k \cdot x_k^t$$

(where α is a weighting factor and x_k is a data vector at time step k) and the EVD of R is searched for at each time step

$$R_k = U_k \cdot \Lambda_k \cdot U_k^t.$$

Here U_k is orthogonal and Λ_k is a diagonal matrix. Previously published updating algorithms, however, suffer from a linear buildup of roundoff error, which makes them impractical when large numbers of recursive updates are needed. The core problem appears to be that U_k gradually looses its orthogonality, when it is iteratively being updated according to

$$\begin{aligned} U_k &= U_{k-1} \cdot Q_k \\ &= Q_1 \cdot Q_2 \cdots Q_k. \end{aligned}$$

Here Q_k is an orthogonal matrix (to working accuracy) which is derived one way or another, depending on the particular updating scheme. In any case, it has been demonstrated [1] that the error propagation for such a product of orthogonal matrices is bounded as

$$\| U_k U_k^t - I \|_F \leq (k + 1) n^{1.5} \epsilon$$

(where $\| \cdot \|_F$ denotes the Frobenius norm). Clearly, if k is large, the error can be significant.

In their paper,[1] DeGroat and Roberts suggest a reorthogonalization scheme where after each update the column vectors of U_k are pairwise reorthogonalized and renormalized as follows (pairwise Gram–Schmidt, PGS):

for $i = 2, \cdots, n$

$$u_i = u_i - (u_i^t \cdot u_{i-1}) \cdot u_{i-1}$$

$$u_i = \frac{u_i}{\| u_i \|_F}$$

end

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Jacobi-Type Algorithms for *LDU* and Cholesky Factorization

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It is demonstrated how conventional algorithms for computing the *LDU* decomposition of a square matrix, or Cholesky factorization for symmetric positive definite matrices, can be reordered into Jacobi-type algorithms. For efficient parallel implementation on a systolic array, the resulting schemes compare favorably with earlier implementations. © 1991 Academic Press, Inc.

INTRODUCTION

In this note it is demonstrated how conventional algorithms for *LU* and *LDU* factorization can be reorganized into Jacobi-type algorithms. First the Jacobi-type algorithm for *LU* decomposition, which largely corresponds to the *QR*D procedure of [4], is derived. This procedure is then transformed into an algorithm for computing the *LDU* decomposition which "preserves symmetry." The latter procedure is therefore suited for computing the Cholesky decomposition as well. The derivation is fairly straightforward, but it has not appeared in the literature before, as far as we know. Up until now, the *LU* and *LDU* factorizations were apparently the only matrix factorizations for which there was no Jacobi-type algorithm available. The advantage of having this type of algorithm available for any matrix decomposition is that then only one type of architecture is needed, which can be used for any operation, where each time only the cell functionality is slightly adapted. In this respect, our approach provides a useful alternative to earlier approaches for systolic *LU* (*LDU*) decomposition: see [2] and the references therein and [1, 3, 5].

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† Senior research assistant with the N.F.W.O. (Belgian National Fund for Scientific Research).

LU DECOMPOSITION

The *LU* decomposition is defined as

$$A = L \cdot U$$

where an $n \times n$ matrix is decomposed as a product of a unit lower and an upper triangular matrix (L resp. U). We refer to [2] for standard algorithms to compute this decomposition. Our aim here is to derive a Jacobi-type algorithm for this decomposition. Such an algorithm is based on locally computed plane transformations and is particularly suited for parallel implementation, e.g., on a systolic array.

Our main source of inspiration is a similar algorithm for computing the *QR* decomposition [4]. This *QR*D procedure is straightforwardly turned into an algorithm for computing the *LU* decomposition, if we use only appropriate row transformations, i.e., embeddings of unit lower triangular 2×2 matrices instead of plane rotations. Briefly, the original matrix $A_{n \times n}$ is reduced to an upper triangular matrix U by applying a sequence of exactly $n(n-1)/2$ such transformations L_i^{-1} to the left, together with column permutations Π_i. Accumulating the left-hand transformations delivers the L matrix, while on the other hand, the accumulated permutations equal the identity. This can be cast as (see [4] for details)

$$A = \underbrace{I \cdot A \cdot I}_{I} = \underbrace{I \cdot L_1 \cdots L_{n(n-1)/2}}_{I} \times \underbrace{L_{n(n-1)/2}^{-1} \cdots L_1^{-1} \cdot A \cdot \Pi_1 \cdots \Pi_{n(n-1)/2}}_{I} \times \underbrace{\Pi_{n(n-1)/2} \cdots \Pi_1 \cdot I}_{I}$$

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GENERALIZATIONS OF THE SINGULAR VALUE AND QR DECOMPOSITIONS*

BART DE MOOR† AND PAUL VAN DOOREN‡

We dedicate this paper to Gene Golub, a true source of inspiration for our work, but also a genuine friend, on the occasion of his 60th birthday

Abstract. This paper discusses multimatrix generalizations of two well-known orthogonal rank factorizations of a matrix: the generalized singular value decomposition and the generalized QR- (or URV-) decomposition. These generalizations can be obtained for any number of matrices of compatible dimensions. This paper discusses in detail the structure of these generalizations and their mutual relations and gives a constructive proof for the generalized QR-decompositions.

Key words. singular value decomposition, QR-factorization, URV-decomposition, complete orthogonal decomposition

AMS(MOS) subject classifications. 15A09, 15A18, 15A21, 15A24, 65F20

1. Introduction. In this paper, we present *multimatrix generalizations* of some well-known orthogonal rank factorizations. We show how the idea of a QR-decomposition (QRD), a URV-decomposition (URVD), and a singular value decomposition (SVD) for one matrix can be generalized to any number of matrices. While generalizations of the SVD for any number of matrices have been derived in [9], one of the main contributions of this paper is the constructive derivation of a generalization for the QRD (or URVD) for any number of matrices of compatible dimensions. The idea is to reduce the set of matrices $A_1, A_2, \ldots, A_k$ to a simpler form using unitary transformations only. Hereby, we avoid explicit products and inverses of the matrices that are involved. We show that these *generalized* QR-*decompositions* (GQRD) can be considered as a preliminary reduction for any *generalized singular value decomposition* (GSVD). The reason is that there is a certain one-to-one relation between the structure of a GQRD and the "corresponding" GSVD, which is explained in detail below.

This paper is organized as follows. In §2, we provide a summary of *orthogonal rank factorizations* for one matrix. We briefly review the SVD, the QRD, and the URVD as special cases. In §3, we give a survey of existing generalizations of the SVD and QRD for two or three matrices. In §4, we summarize the results on GSVDs for any number of matrices of compatible dimensions. Section 5, which contains the main new contribution of this paper, describes a generalization of the QRD and the URVD for any number of matrices. We derive a constructive, inductive proof which shows that a GQRD can be used as a preliminary reduction for a corresponding GSVD. In §6, we analyze in detail the structure of the GQRDs and GSVDs and show that there is a one-to-one relation between the two generalizations. This relation is elaborated in more detail in §7, where we illustrate how a GQRD can be used as a preliminary step in the derivation of a corresponding GSVD.

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On the *QR* Algorithm and Updating the SVD and the *URV* Decomposition in Parallel

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ABSTRACT

A Jacobi-type updating algorithm for the SVD or the *URV* decomposition is developed, which is related to the *QR* algorithm for the symmetric eigenvalue problem. The algorithm employs one-sided transformations, and therefore provides a cheap alternative to earlier-developed updating algorithms based on two-sided transformations. The present algorithm as well as the corresponding systolic implementation is therefore roughly twice as fast as the former method, while the tracking properties are preserved. The algorithm is also extended to the two-matrix *Q*SVD or

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92-33

Structured Total Least Squares and L_2 Approximation Problems*

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ABSTRACT

It is shown how structured and weighted total least squares and L_2 approximation problems lead to a "nonlinear" generalized singular value decomposition. An inverse iteration scheme to find a (local) minimum is proposed. The emphasis of the paper is not on the convergence analysis of the algorithm; rather the purpose is to illustrate its use in numerous applications in systems and control, including total least squares with relative errors and/or fixed elements, inverse singular value problems, an errors-in-variables variant of the Kalman filter, impulse response realization from noisy data, H_2 model reduction, H_2 system identification, and calculating the largest stability radius of uncertain linear systems. Several numerical examples are given.

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Identification of Stable Models in Subspace Identification by Using Regularization

T. Van Gestel, J. A. K. Suykens, P. Van Dooren, and B. De Moor

Abstract—**In subspace identification methods, the system matrices are usually estimated by least squares, based on estimated Kalman filter state sequences and the observed inputs and outputs. For a finite number of data points, the estimated system matrix is not guaranteed to be stable, even when the true linear system is known to be stable. In this note, stability is imposed by using regularization. The regularization term used here is the trace of a matrix which involves the dynamical system matrix and a positive (semi) definite weighting matrix. The amount of regularization can be determined from a generalized eigenvalue problem. The data augmentation method of Chui and Maciejowski is obtained by using specific choices for the weighting matrix in the regularization term.**

Index Terms—**Regularization, stability, subspace identification.**

I. Introduction

The linear combined deterministic–stochastic identification problem is concerned with systems and models of the form[1]

$$x_{k+1} = Ax_k + Bu_k + w_k \tag{1}$$

$$y_k = Cx_k + Du_k + v_k \tag{2}$$

with

$$\mathrm{E}\left(\begin{bmatrix} w_p \\ v_p \end{bmatrix}\begin{bmatrix} w_q^T & v_q^T \end{bmatrix}\right) = \begin{bmatrix} Q & S \\ S^T & R \end{bmatrix}\delta_{pq} \geq 0. \tag{3}$$

The vectors $u_k \in \mathbb{R}^m$ and $y_k \in \mathbb{R}^l$ with discrete-time index k denote the m inputs and l outputs of the system respectively. The n states at the time index k of the system with order n are denoted by the state vector $x_k \in \mathbb{R}^n$. The process noise $w_k \in \mathbb{R}^n$ and the measurement noise $v_k \in \mathbb{R}^l$ are assumed to be zero mean, white Gaussian with covariance matrices as given by (3). The model matrices A, B, C, D and the covariance matrices Q, S, R have appropriate dimensions. Both the deterministic and stochastic identification problem are special cases of the combined identification problem, without noise inputs $w_k = 0$ and $v_k = 0$ in (1)–(3) and no deterministic inputs $u_k = 0$, respectively.

In the last decade, so-called subspace identification methods [13] have been developed to determine the system order $\hat{n}$ of the unknown system (1)–(3) and the estimates $\hat{A}, \hat{B}, \hat{C}, \hat{D}$ (up to a similarity transformation) together with the estimated noise covariances matrices $\hat{Q}, \hat{S}, \hat{R}$, from a large number of observations of the input u_k and the corresponding output y_k generated by the unknown system (1)–(3). Typically, in a first step, Kalman filter state sequences $\hat{X}_i \in \mathbb{R}^{\hat{n}\times j}$ and $\hat{X}_{i+1} \in \mathbb{R}^{\hat{n}\times j}$ of the system are estimated using geometric operations of subspaces spanned by the column or row vectors of block Hankel matrices formed by input–output data. The system order $\hat{n}$ typically has to be estimated by the user from a singular value plot, where j is related to the number of data points, see [13] for details.

The system matrices $(\hat{A}, \hat{B}, \hat{C}, \hat{D})$ of the combined stochastic–deterministic identification problem are identified in the second step by a least squares problem

$$\min_{A,B,C,D} \left\| \begin{bmatrix} \hat{X}_{i+1} \\ Y_{i|i} \end{bmatrix} - \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} \hat{X}_i \\ U_{i|i} \end{bmatrix} \right\|_F^2 \tag{4}$$

with the input sequence $U_{i|i} = [u_i, u_{i+1}, \ldots, u_{i+j-1}] \in \mathbb{R}^{m\times j}$ and the output sequence $Y_{i|i} = [y_i, y_{i+1}, \ldots, y_{i+j-1}] \in \mathbb{R}^{l\times j}$ [13]. Motivated by consistency results [13] for $j \to \infty$, this optimization problem is solved in a least squares sense. However, when identifying on a finite number of data points (finite j), the least squares estimate does not always yield a stable system [2], while often the true linear system is known to be stable. For a finite number of data points, this may, e.g., occur in the presence of high noise levels or when overparameterizing the system by overestimating the system order. A discrete time linear system is called stable when it has all its poles inside the unit disk or when there exists a positive-definite matrix $\hat{P} = \hat{P}^T > 0$ of appropriate dimension such that $\hat{A}\hat{P}\hat{A}^T - \hat{P} < 0$.

In this note, stability of the system is imposed by adding a regularization term to (4). Usually, regularization is obtained by adding the norm $\|\theta\|_2$ of the parameter vector θ to the cost function $J(\theta)$ of the optimization problem [1], [4], [10], [11]. The resulting θ is then obtained as the solution of the minimization problem $\min_\theta J(\theta) + c\|\theta\|_2$. In this note, a new and specific type of regularization term is used: stability is obtained by adding the trace of the product of the system matrix, a positive–semidefinite matrix $W = W^T \geq 0$, and the transpose of the system matrix, $\mathrm{Tr}(\hat{A}W\hat{A}^T)$, to the cost function (4). Upper bounds for the spectral radius are obtained and it is shown that the calculation of the amount of regularization needed to obtain a specific spectral radius boils down to solving a generalized eigenvalue problem.

Also for the stochastic identification problem, the solution $\hat{A}$ of the least squares problem

$$\min_{A,C} \left\| \left[\hat{X}_{i+1}^T \; Y_{i|i}^T\right]^T - [A \; C]^T \cdot \hat{X}_i \right\|_F^2$$

is not always stable. Since the stochastic identification least squares estimate is a special case of the combined estimate (4) with $U_{i|i} = 0$, we restrict ourselves to the more general case of stability of (4).

This note is organized as follows. In Section II, the use of regularization to impose stability is explained. In the companion paper [12], the use of regularization is motivated by simulation results which are compared with the results of [2]. The following notation is used. The eigenvalues and singular values of a square matrix $A \in \mathbb{R}^{n\times n}$ are denoted by $\lambda_i(A)$ and $\sigma_i(A)$ respectively, for $i = 1, \ldots, n$. The spectral radius of A is denoted by $\rho(A) = \max_{i=1,\ldots,n} |\lambda_i(A)|$. The minimal and maximal singular value of A is denoted by $\underline{\sigma}(A)$ and $\overline{\sigma}(A)$, respectively. The trace of the matrix A is denoted by $\mathrm{Tr}(A)$ and the matrix norm $\overline{\sigma}(MAM^{-1})$, with $M \in \mathbb{R}^{n\times n}$ a nonsingular matrix of appropriate dimensions, is denoted by $\|A\|_M$. The Kronecker product of two matrices X and Z is denoted by $X \otimes Z$.

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[1]E denotes the expected value operator and δ_{pq} the Kronecker delta. It is assumed that the process is stationary and ergodic: the equality $\mathrm{E}[a_k b_k^T] = \lim_{j\to\infty}[1/j\sum_{i=0}^{j} a_i b_i^T]$ holds with probability 1.

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On the Stability of the Generalized Schur Algorithm *

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Abstract. The generalized Schur algorithm (GSA) is a fast method to compute the Cholesky factorization of a wide variety of structured matrices. The stability property of the GSA depends on the way it is implemented. In [15] GSA was shown to be as stable as the Schur algorithm, provided one hyperbolic rotation in factored form [3] is performed at each iteration. Fast and efficient algorithms for solving Structured Total Least Squares problems [14, 13] are based on a particular implementation of GSA requiring two hyperbolic transformations at each iteration. In this paper the authors prove the stability property of such implementation provided the hyperbolic transformation are performed in factored form [3].

1 Introduction

The generalized Schur algorithm (GSA) is a fast method to compute the Cholesky decomposition of a wide variety of symmetric positive definite structured matrices, i.e., block Toeplitz and Toeplitz–block matrices, matrices of the form T^TT, where T is a rectangular Toeplitz matrix [9, 7] and to compute the LDL^T factorization of *strongly regular* [1] structured matrices, where L is a triangular matrix and $D = \mathrm{diag}(\pm 1, \ldots, \pm 1)$. The stability property of the GSA depends on the

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A fast algorithm for subspace state-space system identification via exploitation of the displacement structure

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Abstract

Two recent approaches (Van Overschee, De Moor, N4SID, Automatica 30 (1) (1994) 75; Verhaegen, Int. J. Control 58(3) (1993) 555) in subspace identification problems require the computation of the R factor of the QR factorization of a block-Hankel matrix H, which, in general has a huge number of rows. Since the data are perturbed by noise, the involved matrix H is, in general, full rank. It is well known that, from a theoretical point of view, the R factor of the QR factorization of H is equivalent to the Cholesky factor of the correlation matrix $H^{T}H$, apart from a multiplication by a sign matrix. In Sima (Proceedings Second NICONET Workshop, Paris-Versailles, December 3, 1999, p. 75), a fast Cholesky factorization of the correlation matrix, exploiting the block-Hankel structure of H, is described. In this paper we consider a fast algorithm to compute the R factor based on the generalized Schur algorithm. The proposed algorithm allows to handle the rank–deficient case. © 2001 Elsevier Science B.V. All rights reserved.

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Identification of Positive Real Models in Subspace Identification by Using Regularization

Ivan Goethals, Tony Van Gestel, Johan Suykens, Paul Van Dooren, and Bart De Moor

***Abstract*—In time-domain subspace methods for identifying linear-time invariant dynamical systems, the model matrices are typically estimated from least squares, based on estimated Kalman filter state sequences and the observed outputs and/or inputs. It is well known that for an infinite amount of data, this least squares estimate of the system matrices is unbiased, when the system order is correctly estimated. However, for a finite amount of data, the obtained model may not be positive real, in which case the algorithm is not able to identify a valid stochastic model. In this note, positive realness is imposed by adding a regularization term to a least squares cost function in the subspace identification algorithm. The regularization term is the trace of a matrix which involves the dynamic system matrix and the output matrix.**

***Index Terms*—Positive realness, regularization, ridge regression, stochastic systems, subspace identification.**

I. Introduction

In this note, we will consider stochastic systems and models of the form

$$\begin{aligned} x_{k+1} &= Ax_k + wk \\ y_k &= Cx_k + v_k \end{aligned} \tag{1}$$

with

$$\mathcal{E}\left\{\begin{bmatrix} w_p \\ v_p \end{bmatrix}\begin{bmatrix} w_q^T & v_q^T \end{bmatrix}\right\} = \begin{bmatrix} Q & S \\ S^T & R \end{bmatrix}\delta_{pq} \geq 0 \tag{2}$$

where $\mathcal{E}\{\cdot\}$ denotes the expected value operator and δ_{pq} the Kronecker delta. The elements of the vector $y_k \in \mathbb{R}^l$ are given observations at the discrete-time index k of the l outputs of the system. The vector $x_k \in \mathbb{R}^n$ is the unknown state vector at time k. The unobserved process and measurement noise $w_k \in \mathbb{R}^n$ and $v_k \in \mathbb{R}^l$ are assumed to be white, zero mean, Gaussian with covariance matrices as given in (2). The system matrices A, C and the covariance matrices Q, S, and R have appropriate dimensions.

Denoting the output covariance matrices as $\Lambda_m = \mathcal{E}\{y_{k+m}y_k^T\}$, and the cross-covariance matrix between the states and the observations as $G = \mathcal{E}\{x_{k+1}y_k^T\}$, one can derive that $\Lambda_m = CA^{m-1}G$, $\Lambda_{-m} = \Lambda_m^T$, $m \geq 1$. Hence, the output covariances can be considered as Markov parameters of a deterministic linear time invariant system with system matrices (A, G, C, D) where $D + D^T = \Lambda_0$. Throughout this note, we will refer to (A, G, C, D) as the "covariance model." The spectral density $\Phi(z)$ of the system (1) can be expressed in terms of the covariance model as $\Phi(z) = S(z) + S^T(z^{-1})$ with $S(z) = D + C(zI_n - A)^{-1}G$ and is assumed to be positive for all z on the unit circle, in which case the model (A, G, C, D) is called positive real.

Stochastic subspace identification methods [1] make extensive use of the covariance model. Typically they start by making an estimate $(\hat{A}, \hat{G}, \hat{C}, \hat{D})$ based on available measurements. In a second step the covariance model is then transformed into a so-called forward innovation model which is statistically equivalent to a model of the form (1). However, it is known that the second step may fail if the estimated model $(\hat{A}, \hat{G}, \hat{C}, \hat{D})$ is not positive real due to modeling errors (see, for instance, [2]). In such cases, no physically meaningful model will be returned by the subspace identification algorithm.

In recent years, several modifications to the standard stochastic subspace identification algorithms have been suggested to solve the positive realness problem. This, however, at the cost of introducing a small bias in the obtained solution. In this note, we impose positive realness by adding a regularization term to a least squares cost function appearing in most stochastic subspace identification algorithms. Although a bias is still introduced, the regularization approach will be seen to outperform those reported in the literature.

The outline of this note is as follows. In Section II, the stochastic subspace identification algorithm will be outlined, and its problems with positive realness will be described. A proposal for a technique to impose positive realness on an identified covariance model will be given in Section III, the performance of this technique will be compared to that of various existing ones in Section IV, and a real-life example will be introduced in Section V. Finally, the conclusions will be drawn in Section VI.

II. Subspace Identification

Stochastic subspace identification algorithms typically start by calculating Kalman filter state sequences $\hat{X}_i \in \mathbb{R}^{n \times j}$ and $\hat{X}_{i+1} \in \mathbb{R}^{n \times j}$ of the system and an estimate of the system order n directly from output data. This is done using geometric operations of subspaces spanned by the column or row vectors of block Hankel matrices. For instance, the output data block Hankel matrix $Y_p = Y_{0,i-1}$ of past outputs is constructed from the observations $y_0, y_1, \ldots, y_{i+j-2}$ as follows:

$$Y_{0,i-1} = \begin{bmatrix} y_0 & y_1 & \cdots & y_{j-1} \\ y_1 & y_2 & \cdots & y_j \\ \vdots & \vdots & & \vdots \\ y_{i-1} & y_i & \cdots & y_{i+j-2} \end{bmatrix} \tag{3}$$

where i, the number of block rows in the block Hankel matrix, and j, the number of columns, are user defined dimensions with typically $i \ll j$. In many cases, i will be chosen first whereafter j is adapted so as to use all available observations in the block Hankel matrices.

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Editorial

Numerical Linear Algebra in Signal Processing Applications

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The cross-fertilization between numerical linear algebra and digital signal processing has been very fruitful in the last decades. In particular, signal processing has been making increasingly sophisticated use of linear algebra on both theoretical and algorithmic fronts. The interaction between them has been growing, leading to many new algorithms. In particular, numerical linear algebra tools, such as eigenvalue and singular value decomposition and their higher-extensions, least squares, total least squares, recursive least squares, regularization, orthogonality and projections, are the kernels of powerful and numerically robust algorithms in many signal processing applications.

This special issue contains contributions written by experts of signal processing, computer engineering, and numerical analysis, providing an account of the main results in this interdisciplinary field. Most of the papers are devoted to applications of numerical linear algebra algorithms for solving signal processing problems. Nevertheless, few of them are more theoretically oriented, and describe algorithms for solving linear algebra problems involving structured matrices and tensors, frequently encountered in a variety of signal processing applications.

In the paper by H. Reza Bahrami et al., the effect of eigenvalues distribution of spatial correlation matrices on the capacity of frequency-flat and frequency-selective channels is first investigated. Then, a practical scheme, known as linear precoding, is introduced. It can enhance the ergodic capacity of the channel by changing the eigenstructure of the channel, applying a linear transformation. The structures of precoders using eigenvalue decomposition and linear algebra techniques are derived and their similarities from an algebraic point of view are shown.

Numerical methods for finding the maximal symmetric positive definite solution of the nonlinear matrix equation $X = Q + LX^{-1}L^T$, where Q is symmetric positive definite and L is nonsingular, are studied in the article by P. Benner and H. Faßbender. Such equations arise, for instance, in the analysis of stationary Gaussian reciprocal processes over a finite interval. Its unique largest positive definite solution coincides with the unique positive definite solution of a related discrete-time algebraic Riccati equation.

I. Drori, in his paper, presents a method which takes advantage of the sparsity of the wavelet representation of the nuclear magnetic resonance (NMR) spectra and reconstructs the spectra from partial random measurements of its free induction decay. This is done by solving an optimization problem. In the settings of interest, the underlying solution is sparse with a few nonzero entries. For large practical systems, a good approximation of the solution can be obtained by iterative thresholding algorithms, running much more rapidly than general solvers. The applicability of this approach to fast multidimensional NMR spectroscopy is shown.

The paper by P. Favati et al. deals with image restoration problems. Among the many regularization methods used for handling the problem, iterative methods have been shown to be effective. The authors propose inverse preconditioners with a band Toeplitz structure for solving linear systems having band block Toeplitz structure with band Toeplitz blocks,

Conference papers

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Updating Singular Value Decompositions. A parallel implementation.

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Abstract

In this paper, we give an overview of a few recently obtained results regarding algorithms and systolic arrays for updating singular value decompositions. The Ordinary SVD as well as the Product SVD and the Quotient SVD will be discussed.

The updating algorithms consist in an interlacing of QR-updatings and a Jacobi-type SVD-algorithm applied to the triangular factor(s). At any time step an approximate decomposition is computed from a previous approximation, with a limited number of operations ($O(n^2)$). When combined with exponential weighting, these algorithms are seen to be highly applicable to tracking problems. Furthermore, they can elegantly be mapped onto systolic arrays, making use of slight modifications of well known systolic implementations for the matrix-vector product, the QR-updating and the SVD.

1 Introduction

Let A be an $m \times n$ matrix, with $(m \geq n)$. The *Ordinary Singular Value Decomposition* (OSVD) is a factorization of A into a product of three matrices

$$A_{m\times n} = U_{m\times n}\Sigma_{n\times n}V^t_{n\times n}$$

where $U^tU = I$, $V^tV = I$, and Σ is a diagonal matrix, with the singular values on the main diagonal.

The updating problem considered here, consists in computing the OSVD of the modified matrix

$$\begin{bmatrix} \lambda.A \\ a^t \end{bmatrix} = U^\star_{(m+1)\times n}\Sigma^\star_{n\times n}V^{\star t}_{n\times n}$$

Combined Jacobi-type Algorithms in Signal Processing

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Abstract

A brief overview is given of recently developed parallel algorithms in the area of signal processing and systems theory and control. Firstly, approximate $O\{n^2\}$ algorithms are described for *SVD updating* problems, which are then shown to be stable and fairly accurate. Use is made of Jacobi-type SVD algorithms mainly, plus additional matrix operations such as triangular updates, matrix-vector multiplications, etc. This *combined Jacobi approach* results in regularly structured algorithms, which are efficiently implemented on parallel architectures such as systolic arrays. Similar developments have led to efficient algorithms for *Kalman filtering*, for solving *Riccati and Lyapunov equations*, for *Recursive Least Squares*, etc.

1 Introduction

Linear algebra and matrix computation play a central role in modern systems theory and digital signal processing. Representative areas in which matrix computation is important include beamforming, direction finding, spectrum analysis, image processing, systems identification, robust control, etc. As problems have grown in difficulty and complexity, numerical issues such as error propagation and problem sensitivity have become more important. The impact of *numerical linear algebra* or *numerical analysis* is apparent through the increased use of orthogonal techniques such as QR factorizations and singular value decompositions (SVD's). The SVD has become more or less *the* analytical tool for statistics, control engineering, etc., where numerous theoretical concepts have been reformulated in the language of the SVD [GoVl].

A main point of focus is *fast adaptive SVD* or *SVD updating* for real time applications. Previously described techniques for SVD row updating mostly reduce to solving the corresponding rank-one modified symmetric eigenvalue problem [BNS, BN, Go]. In each time step an *exact* decomposition is computed from a previous decomposition. The operation count is $O\{n^3\}$ where n is the problem size. For many practical applications this is excessive. Moreover, these procedures are apparently unstable.

As an alternative to these methods, we derived an SVD updating procedure as a combination of a Jacobi-type SVD procedure [Lu2] with QR updating [GK]. Apparently only a few SVD steps after each QR update suffice in order to restore an acceptable approximation for the SVD. This updating procedure is shown to be *cheap* –$O\{n^2\}$, similar to merely QR updating– *fairly accurate* and *particularly suited for parallel implementation*. Furthermore this procedure is easily extended to various generalized SVD updating problems –QSVD updating for instance– problems which had not been looked at before, as far as we know.

Our approach to SVD updating mainly consists in combining the Jacobi-type algorithm for the SVD with a few additional elementary matrix operations. In general, a broad range of algorithms can be pieced together with a fairly small sequence of key matrix algorithms –Jacobi-type algorithms mainly– especially orthogonal reductions (SVD's and QR decompositions), matrix inversions, matrix multiplications or matrix-vector multiplications, triangular backsolves, etc. Elementary (Jacobi-type) algorithms are then elegantly assembled into combined (Jacobi-type) algorithms. Such *combined algorithms* have been derived for *Kalman filtering*, for solving *Riccati and Lyapunov equations*, for *Recursive Least Squares*, etc.

Finally, for applications with substantial computational requirements such as speech and radar processing, *parallel algorithms and architectures* are indispensable, especially when a real time implementation is aimed at. Systolic or wavefront arrays then provide a means of exploiting large amounts of parallelism and hence achieving significant speed-ups. While practical parallel algorithms for most of the key matrix operations are by now available, implementing combined algorithms appears to be a major problem. We developed *systolic arrays* for the above mentioned combined algorithms.

The main points of focus are thus (i) fast algorithms for

SVD updating for tracking slowly time-varying systems. A parallel implementation.

Marc Moonen, Paul Van Dooren, Joos Vandewalle

Abstract

A procedure is presented for updating the singular value decomposition of a matrix as new rows are appended successively. The updating consists in an interlacing of QR-updatings and a Jacobi-type SVD-algorithm applied to the triangular factor. At any time step an approximate decomposition is computed from a previous approximation, with a limited number of operations ($O(n^2)$). When combined with exponential weighting, the algorithm is seen to be highly applicable to tracking problems, as will be demonstrated with an example. Furthermore, this algorithm can elegantly be mapped onto a systolic array, making use of slight modifications of well known systolic implementations for the matrix-vector product, the QR-updating and the SVD.

1 Introduction

Common techniques for updating the singular value decomposition (SVD) of a matrix after appending new rows, mostly reduce to solving the corresponding modified symmetric eigenvalue problem [2, 3, 5]. A drawback is the necessary knowledge of the *exact* original eigenstructure, in order to compute the updated eigenstructure. On the one hand, this considerably increases the computational load (e.g. in an on-line environment, where at each time step an *exact* updating is thus to be performed), while on the other, round-off errors are likely to accumulate unboundedly.

In this paper, we present an SVD updating procedure that interlaces a Jacobi-type SVD algorithm [1, 7] with a QR-updating each time a new row is to be worked in. After each QR-update, the SVD algorithm reduces the R-factor to an approximately diagonal matrix, by applying a sequence of plane rotations. It may be appropriate to try and perform only a fixed number of rotations (e.g. $n-1$, see below) on the triangular factor after each QR-update. This results in a seemingly *non-iterative* algorithm that at any time step outputs an *approximate decomposition* computed from a previous approximation, with only a limited number of operations (viz. $O(n^2)$). The crux is then to show how only a few SVD-steps after each QR-update can restore an acceptable approximation at every stage.

When combined with exponential weighting, this algorithm is seen to be highly applicable to *tracking problems*. Furthermore, the updating algorithm can be mapped onto a *systolic array* with $O(n^2)$ parallelism for $O(n^2)$ operations, by appropriately combining systolic implementations for the matrix-vector product, the QR-updating and the SVD.

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Numerical Linear Algebra, Digital Signal Processing and Parallel Algorithms

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SLICOT,

A SUBROUTINE LIBRARY IN CONTROL AND SYSTEMS THEORY.

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Abstract

Past initiatives with respect to realising control libraries are analyzed. A new collaborative initiative is introduced. The design of a new control library SLICOT is presented and the first release of this library is discussed.

Keywords

Computer-aided control system design, interactive computing, control engineering computer applications, control libraries.

1. Introduction and history

In recent years there has been an increasing interaction between the fields of numerical linear algebra and of control and systems theory. System theorists had to turn their attention to advanced numerical software for solving their problems as they found that their straightforward methods did not work well when applied on harder problems such as large scale systems and ill-posed problems. Numerical analysts have started to focus on the linear algebra problems arising in linear systems theory. This cross-fertilisation has resulted in a considerable number of novel techniques both in terms of speed and accuracy; see Van Dooren (1989). But many problems are still waiting for an adequate algorithm which is both fast and accurate and at the same time respects the structure of the problem. The growing number of people involved in this interdisciplinary area of research shows the relevance of the area. A more explicit indication of this is the importance that the field has acquired in industrial environments: advanced control techniques are not only being applied in production processes but are also built into actual products such as compact discs and medical equipment.

User-friendly and powerful tools for the analysis and design of complex systems became available with the advent of CACSD programs in the last decade; see Van den Boom (1988) and Rimvall c.s. (1985). Such a CACSD tool is a complicated hierarchical software structure, where the libraries containing the mathematical and control algorithms are usually placed on lower levels of the hierarchy. Moreover, the libraries constitute only a small part of the total software volume of the CACSD program. Nevertheless the quality of the outcome of the CACSD program is fully determined by the quality of these libraries.

Over the last ten years several efforts have been initiated to produce software libraries of basic subroutines dealing with various analysis or design problems in control and systems theory. The Scandinavian control library (Elmqvist c.s., 1976; Wieslander, 1977) and the Swiss control library AUTLIB (Cellier c.s., 1977) were the first initiatives in the field. However, these libraries did not reach maturity. A British cooperation led to the realization of the control library SLICE which contains a set of almost 40 control routines, see Denham c.s. (1981), Denham (1985) and Williams (1986). A revised version of SLICE was issued by NAG in 1987. The Benelux Working Group on Software (WGS) has realised the prototype control library SYCOT, see WGS (1983). The libraries SLICE and SYCOT form the basis of the SLICOT library to be discussed in the sequel. The German control library RASP offers about 250 subroutines classified in 7 chapters, mainly for control, and some 20 main programs for several chapters of control and systems theory; see Grübel (1983) and Grübel c.s. (1990). RASP is a large library and has indeed reached maturity.

Least Squares Support Vector Machine Classifiers: a Large Scale Algorithm *

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Abstract

Support vector machines (SVM's) have been introduced in literature as a method for pattern recognition and function estimation, within the framework of statistical learning theory and structural risk minimization. A least squares version (LS-SVM) has been recently reported which expresses the training in terms of solving a set of linear equations instead of quadratic programming as for the standard SVM case. In this paper we present an iterative training algorithm for LS-SVM's which is based on a conjugate gradient method. This enables solving large scale classification problems which is illustrated on a multi two-spiral benchmark problem.

Keywords. Support vector machines, classification, neural networks, RBF kernels, conjugate gradient method.

1 Introduction

Support vector machines have been introduced in [16] for solving pattern recognition and nonlinear function estimation problems. In this method one maps the data into a higher dimensional input space in which one constructs an optimal separating hyperplane. As kernel functions one can use polynomials, splines, radial basis function networks and multilayer perceptrons. For the mapping into the higher dimensional input space and kernels one makes use of Mercer's condition. While classical neural network techniques suffer from the existence of many local minima [1, 3, 8, 19], SVM solutions are obtained from quadratic programming problems possessing a global solution. Kernel functions and parameters can be chosen such that a bound on the VC dimension is minimized [3, 16, 17, 18, 15]. Being based on the structural risk minimization principle and capacity concept with pure combinatorial definitions, the quality and complexity of the SVM solution does not depend directly on the dimensionality of the input space [16, 17, 18]. Links between SVM's, regularization theory and sparse approximations have been shown in [12, 6].

In the support vector method of function estimation one typically employs Vapnik's epsilon insensitive loss function or Huber's loss function. In [14] a least squares version of SVM's for classification has been proposed, which is related to the LS version for function estimation reported in [10]. In this LS-SVM version one finds the solution by solving a linear system instead of quadratic programming. This is due to the use of equality instead of inequality constraints in the problem formulation. In [2, 5, 13] such linear systems have been called augmented systems or Karush-Kuhn-Tucker (KKT) systems and their numerical stability has been investigated. In this paper we present an iterative solution to LS-SVM's based on the conjugate gradient method [7]. This method enables solving large scale classification problems. As an example we show the excellent performance on a multi two-spiral benchmark problem, which is known to be a difficult test case for neural network classifiers [9].

This paper is organized as follows. In Section 2 we discuss LS-SVM classifiers. In Section 3 we present an iterative method for training large scale LS-SVM's. In Section 4 an illustrative example is given on a multi two-spiral benchmark problem.

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Imposing Stability in Subspace Identification by Regularization

Tony Van Gestel[1], Johan A.K. Suykens[1],
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Abstract –In subspace methods for linear system identification, the system matrices are usually estimated by least squares, based on estimated Kalman filter state sequences and the observed inputs and outputs. For an infinite number of data points and a correct choice of the system order, this least squares estimate of the system matrices is unbiased. However, when using subspace identification on a finite number of data points, the estimated model can become unstable, for a given deterministic system which is known to be stable. In this paper, stability of the estimated model is imposed by adding a regularization term to the least squares cost function. The regularization term used here is the trace of a matrix which involves the dynamical system matrix and a positive (semi-)definite weighting matrix. The amount of regularization needed can be determined by solving a generalized eigenvalue problem. It is shown that the so-called data augmentation method proposed by Chui and Maciejowski corresponds to adding regularization terms with specific choices for the weighting matrix. The choice of the identity matrix for the weighting matrix is motivated by simulation results.

Keywords: stability, subspace identification, regularization, ridge regression

1 Introduction

The linear combined deterministic-stochastic identification problem is concerned with systems and models of the form:

$$x_{k+1} = Ax_k + Bu_k + w_k \quad (1)$$
$$y_k = Cx_k + Du_k + v_k \quad (2)$$

with[1]

$$\mathrm{E}\left(\begin{bmatrix} w_p \\ v_p \end{bmatrix}\begin{bmatrix} w_p \\ v_p \end{bmatrix}^T\right) = \begin{bmatrix} Q & S \\ S^T & R \end{bmatrix}\delta_{pq} \geq 0. \quad (3)$$

The vectors $u_k \in \mathbb{R}^m$ and $y_k \in \mathbb{R}^l$ with discrete time index k denote the m inputs and l outputs of the system respectively. The n states at the time index k of the system with order n are denoted by the state vector $x_k \in \mathbb{R}^n$. The process noise $w_k \in \mathbb{R}^n$ and the measurement noise $v_k \in \mathbb{R}^l$ are assumed to be zero mean, white Gaussian with covariance matrices as given by (3). The model matrices A, B, C, D and the covariance matrices Q, S, R have appropriate dimensions. Both the deterministic and stochastic identification problem are special cases of the combined identification problem, without noise inputs $w_k = 0$ and $v_k = 0$ in (1)-(3) and no deterministic inputs $u_k = 0$, respectively.

The system identification problem is stated as follows: *given* a large number of observations of the input u_k and the corresponding output y_k generated by the unknown system (1)-(3), *determine* the system order $\hat{n}$ of the unknown system (1)-(3) and the estimates $\hat{A}, \hat{B}, \hat{C}, \hat{D}$ up to within a similarity transformation together with the estimated noise covariances matrices $\hat{Q}, \hat{S}, \hat{R}$ so that the second order statistics of the output of the model *and* of the given output are equal (or equivalent in the sense of Faurre [8]).

In the last decade, so-called subspace identification methods [8] have been developed. Typically, in a first step, Kalman filter state sequences $\hat{X}_i \in \mathbb{R}^{\hat{n}\times j}$ and $\hat{X}_{i+1} \in \mathbb{R}^{\hat{n}\times j}$ of the system are estimated directly from input-output data using geometric operations of subspaces spanned by the column or row vectors of block Hankel matrices formed by input-output data. The output data block Hankel matrix $Y_{0|i-1}$ is constructed from the observations $y_0, y_1, \ldots, y_{i+j-2}$ as follows:

$$Y_{0|i-1} = \begin{bmatrix} y_0 & y_1 & \cdots & y_{j-1} \\ y_1 & y_2 & \cdots & y_j \\ \cdots & \cdots & \cdots & \cdots \\ y_{i-1} & y_i & \cdots & y_{i+j-2} \end{bmatrix},$$

where i is a user defined dimension with $i \ll j$ and the subscript $0|i-1$ denotes the time indices of the

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[1]E denotes the expected value operator and δ_{pq} the Kronecker delta. It is assumed that the process is stationary and ergodic: $\mathrm{E}[a_k b_k^T] = \lim_{j\to\infty}[\frac{1}{j}\sum_{i=0}^{j} a_i b_i^T]$.

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FAST IMPLEMENTATION OF THE QR FACTORIZATION IN SUBSPACE IDENTIFICATION

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Two recent approaches [4, 14] in subspace identification problems require the computation of the R factor of the QR factorization of a block–Hankel matrix H, which, in general has a huge number of rows. Since the data are perturbed by noise, the involved matrix H is, in general, full rank. It is well known that, from a theoretical point of view, the R factor of the QR factorization of H is equivalent to the Cholesky factor of the correlation matrix $H^T H$, apart from a multiplication by a sign matrix. In [12] a fast Cholesky factorization of the correlation matrix, exploiting the block–Hankel structure of H, is described. In this paper we consider a fast algorithm to compute the R factor based on the generalized Schur algorithm. The proposed algorithm allows to handle the rank–deficient case.

Keywords: identification methods; least squares solutions; multivariable systems; singular values.

INTRODUCTION

Subspace based system identification techniques have been studied intensively in the last decades [4]. The major drawbacks of these direct state–space identification techniques are the high computation and storage costs.

Let u_k and y_k be the m–dimensional input vector and the l–dimensional output vector, respectively, of the basic linear time–invariant state space model

$$\begin{aligned} x_{k+1} &= Ax_k + Bu_k + w_k, \\ y_k &= Cx_k + Du_k + v_k, \end{aligned}$$

where x_k is the n–dimensional state vector at time k, $\{w_k\}$ and $\{v_k\}$ are state and output disturbances or noise sequences, and A, B, C and D are unknown real matrices of appropriate dimensions.

For non–sequential data processing, the $N \times 2(m+l)s$, $N \gg 2(m+l)s$, matrix $H = [U_{1,2s,N}^T Y_{1,2s,N}^T]$ is constructed, where $U_{1,2s,N}$ and $Y_{1,2s,N}$ are block–Hankel matrices defined in terms of the input and output data, respectively,

$$U_{1,2s,N} = \begin{bmatrix} u_1 & u_2 & u_3 & \cdots & u_N \\ u_2 & u_3 & u_4 & \cdots & u_{N+1} \\ u_3 & u_4 & u_5 & \cdots & u_{N+2} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ u_{2s} & u_{2s+1} & u_{2s+2} & \cdots & u_{N+2s-1} \end{bmatrix},$$

$$Y_{1,2s,N} = \begin{bmatrix} y_1 & y_2 & y_3 & \cdots & y_N \\ y_2 & y_3 & y_4 & \cdots & y_{N+1} \\ y_3 & y_4 & y_5 & \cdots & y_{N+2} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ y_{2s} & y_{2s+1} & y_{2s+2} & \cdots & y_{N+2s-1} \end{bmatrix}.$$

Then the R factor of a QR factorization $H = QR$, is used for data compression. In [12] a fast Cholesky factorization of the correlation matrix, exploiting the block–Hankel structure of H, is described. In this paper we consider a fast algorithm to compute the R factor of the QR factorization of H based on the generalized Schur algorithm, exploiting its *displacement structure*. The implementation of the algorithm depends, in particular, on the involved matrix. The paper is organized as follows. First the generalized Schur algorithm to compute the Cholesky factor of a symmetric positive definite matrix is described. Then the generalized Schur algorithm applied to the matrix H is considered. The rank–deficient case is also discussed. Finally, some numerical experiments are reported.

THE GENERALIZED SCHUR ALGORITHM FOR SYMMETRIC POSITIVE DEFINITE MATRICES

In this section the key properties of the generalized Schur algorithm to compute the Cholesky factor of a symmetric positive definite (s.p.d.) matrix, which will be used in the next section, are summarized. More details can be found in [7, 8].

Let A and Z be a s.p.d. matrix and a shift matrix of order

IDENTIFYING POSITIVE REAL MODELS IN SUBSPACE IDENTIFICATION BY USING REGULARIZATION

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Abstract: This paper deals with the lack of positive realness of identified models that may be encountered in many stochastic subspace identification procedures. Lack of positive realness is an often neglected, but important problem. Subspace identification algorithms fail to return a valid linear model if the so-called covariance model, which is obtained from an intermediate realization step in the subspace identification algorithm, is not positive real. The main contribution of this paper is to introduce a regularization approach to impose positive realness on the covariance model. It is shown that positive realness can be imposed by adding a regularization term to a least squares cost function appearing in the subspace identification procedure.

Keywords: stochastic systems, subspace methods, robustness, regularization

1. INTRODUCTION

In this paper, we will consider stable systems and models of the form:

$$\begin{aligned} x_{k+1} &= Ax_k + w_k, \\ y_k &= Cx_k + v_k, \end{aligned} \tag{1}$$

with

$$\mathcal{E}\left\{ \begin{bmatrix} w_p \\ v_p \end{bmatrix} \begin{bmatrix} w_q^T & v_q^T \end{bmatrix} \right\} = \begin{bmatrix} Q & S \\ S^T & R \end{bmatrix} \delta_{pq} \geq 0, \tag{2}$$

where $\mathcal{E}\{\cdot\}$ denotes the expected value operator and δ_{pq} the Kronecker delta. It is assumed that $\mathcal{E}\left\{ \begin{bmatrix} w_p \\ v_p \end{bmatrix} x_k^T \right\} = 0, \forall p \geq k$. The elements of the vector $y_k \in \mathbb{R}^l$ are given observations at the discrete time index k of the l outputs of the system. The vector $x_k \in \mathbb{R}^n$ is the unknown state vector at time k. The unobserved process and measurement noise $w_k \in \mathbb{R}^n$ and $v_k \in \mathbb{R}^l$ are assumed to be white, zero mean, Gaussian with covariance matrices as given in (2). The system matrices A, C and the covariance matrices Q, S, and R have appropriate dimensions.

Stochastic subspace identification methods are ideally suited to identify models of the form (1). Typically, in a first step the measured output sequence $y_0, y_1, \ldots, y_{N-1}$ is stored in block Hankel matrices containing a user defined number of block rows i, and a certain number of columns j, so that $N = 2i + j - 1$, see (Van Overschee and De Moor, 1993)(Van Overschee and De Moor, 1996) for an extensive survey of this procedure. Kalman filter state sequences $\hat{X}_i \in \mathbb{R}^{n \times j}$ and $\hat{X}_{i+1} \in \mathbb{R}^{n \times j}$ of the system and an estimate of the system order $\hat{n}$ are then obtained by using geometric operations of subspaces spanned by the column and row vectors of these Hankel matrices.

In a second step, a so called covariance model $(\hat{A}, \hat{G}, \hat{C}, \hat{D})$, is estimated, where $\hat{G}$ is an estimate for the covariance matrix between states and observations $G = \mathcal{E}\left\{x_{k+1} y_k^T\right\}$ and $\hat{D} = \frac{\hat{\Lambda}_0}{2}$ is an estimate for $\frac{\Lambda_0}{2}$, with $\Lambda_m = \mathcal{E}\left\{y_{k+m} y_k^T\right\}, m \geq 0$ the output

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PhD Thesis

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FAST AND RELIABLE ALGORITHMS FOR STRUCTURED TOTAL LEAST SQUARES AND RELATED MATRIX PROBLEMS

Jury:
Prof. dr. ir. J. Berlamont, voorzitter
Prof. dr. ir. S. Van Huffel, promotor
Prof. dr. ir. P. Van Dooren, promotor
Prof. dr. D. A. Bini, (Univ. Pisa, Italy)
Prof. dr. ir. A. Bultheel,
Prof. dr. ir. B. De Moor,
Prof. dr. ir. M. Van Barel.

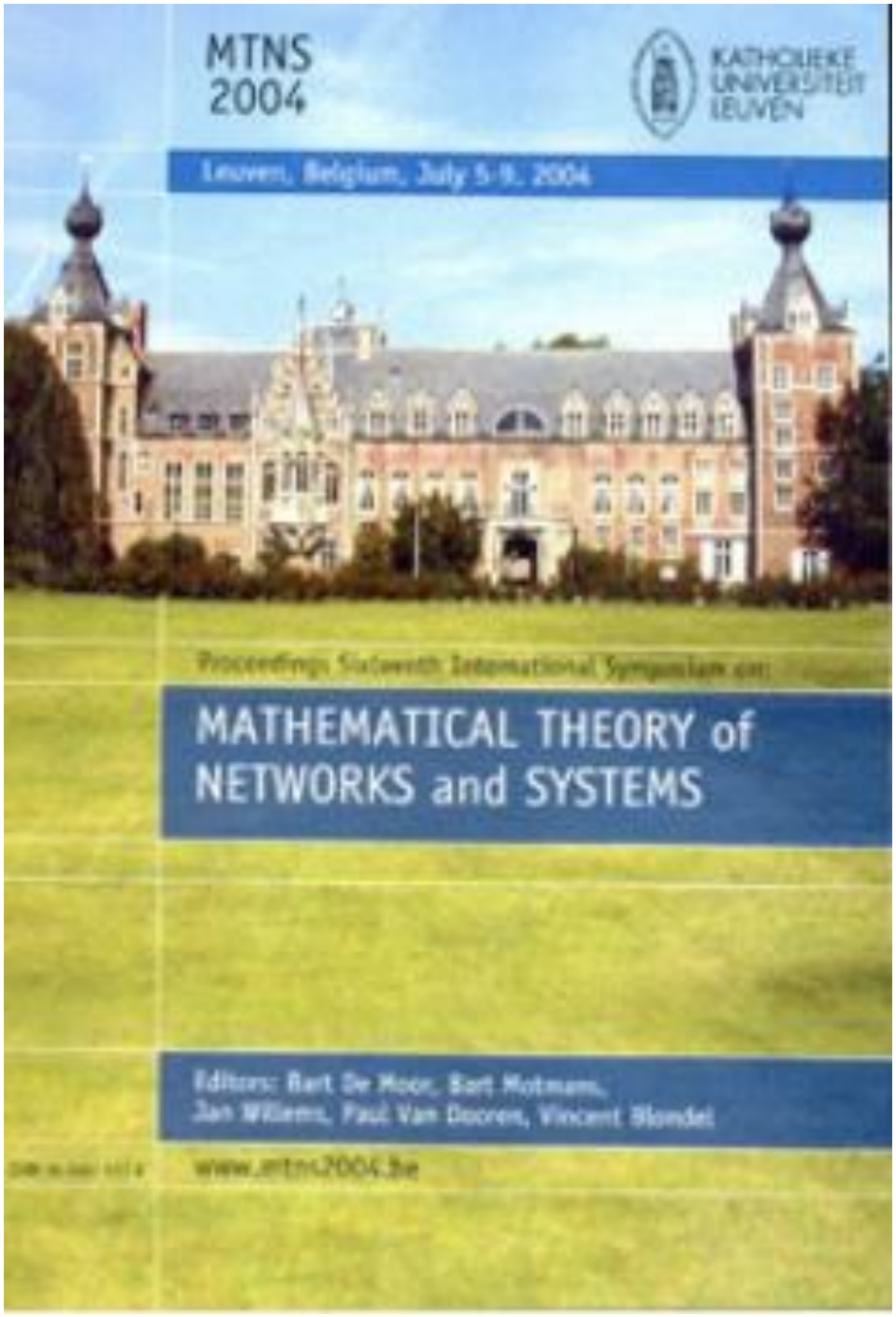
Proefschrift voorgedragen tot
het behalen van het doctoraat
in de toegepaste wetenschappen

door

Nicola MASTRONARDI

U.D.C. 519.654

May 2001


MTNS
2004
KATHOLIEKE UNIVERSITEIT LEUVEN
Leuven, Belgium, July 5-9, 2004
Proceedings Sixteenth International Symposium on
MATHEMATICAL THEORY of NETWORKS and SYSTEMS
Editors: Bart De Moor, Bart Motmans,
Jan Willems, Paul Van Dooren, Vincent Blondel
www.mtns2004.be

After dinner presentation, Paul Van Dooren 75 (Selva di Fasano, Bari, July 9, 2025)

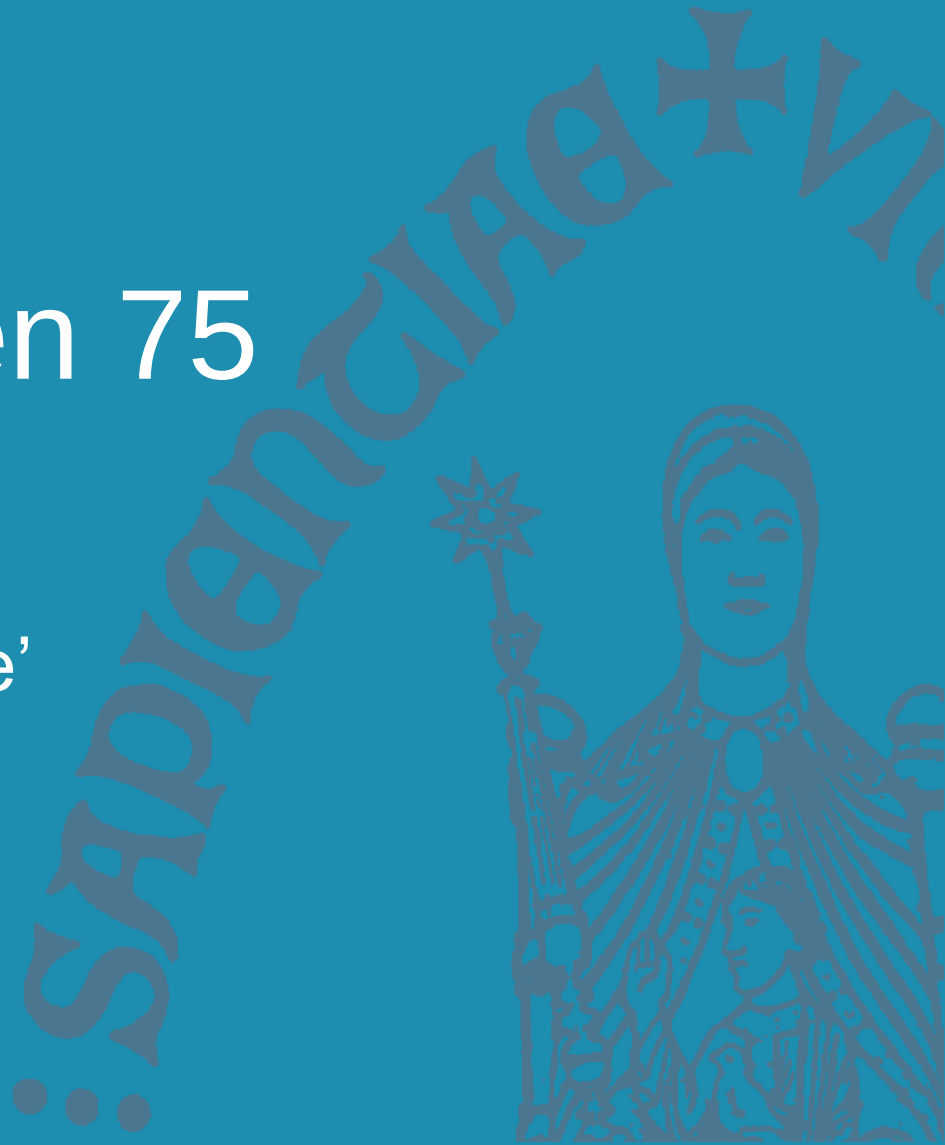
KU LEUVEN

A tribute to

Paul Van Dooren 75

by your colleague
‘et ami quand même’

Bart De Moor



Outline

1. Years in Tienen
2. Years in Leuven
3. Our common network
4. Stanford
5. Working in secrecy and conspiracy
6. Remembrance Days
7. Paul, a friend indeed

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An interview with Paul Van Dooren

Chahlaoui, Younes

2011

MIMS EPrint: **2011.74**

Manchester Institute for Mathematical Sciences
School of Mathematics

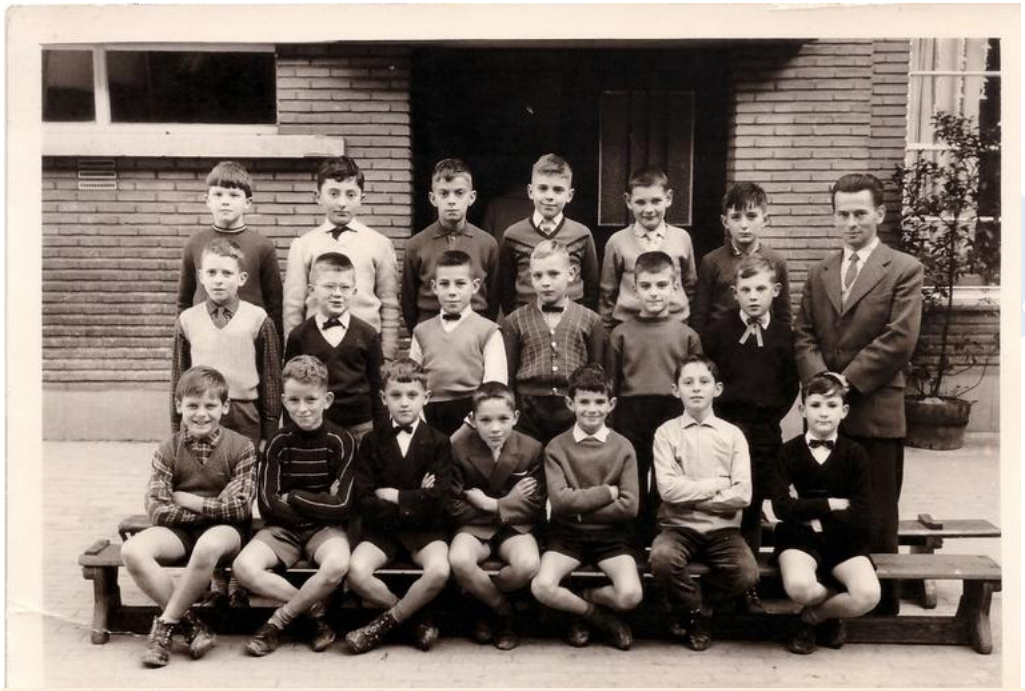
KU LEUVEN

YC: Where was the elementary school?

PVD: In Tienen in Belgium and the secondary school or high school as they say sometimes in English, was also in Tienen. I did well, especially in mathematics, even though I was not in the right orientation. I was not registered as a student of mathematics, but rather of Latin, Greek and so I had only 3 hours per week of mathematics, but that was one of the courses I liked most actually.

KU LEUVEN



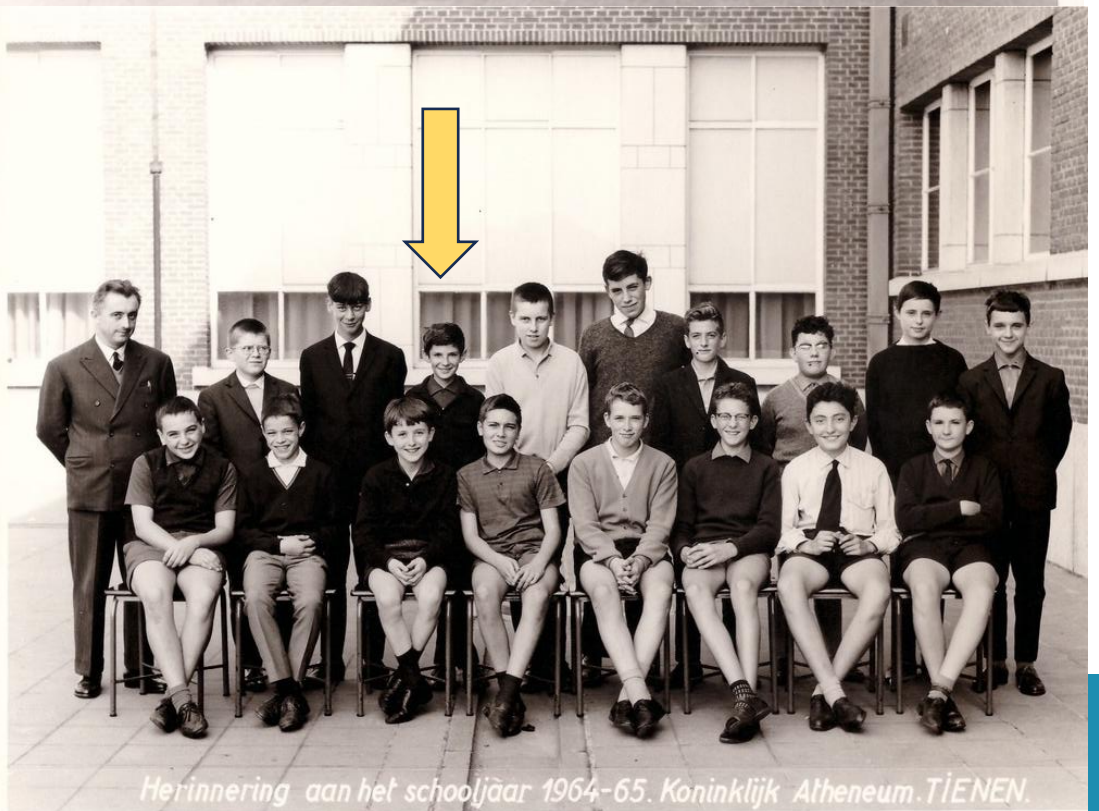



Herinnering aan het schooljaar 1964-65. Koninklijk Atheneum. TIENEN.








Herinnering aan het schooljaar 1964-65. Koninklijk Atheneum. TIENEN.



Eerste Latijn-Grieks

Debrye Paul	737 op I000	000
Es Hilaire	7I2	
Sterckx Guido	783	
Vandooren Paul	8I0	

Eerste Latijn-Wiskunde

Doperé Frans	773 op I000	
Hoylaerts André ja	607	

Eerste Latijn-Wetenschappen

Allard Frans	750 op I000	
Dehaen Eddy ja	627	
Heusdens Omer	657	
Hoebregs Hubert ja	6I3	
Kempeneers Jacques	684	
Petes Jos	733	
Simons Johan	738	
Veroeveren Piet	79I	
Vranckx Arthur	837	

BIJZONDERE BELONING VAN DE REGERING

Ingeval een leerling, Prijs van Uitmuntendheid in Retorica of in de eersten, in een Rijksinrichting van het Middelbaar Onderwijs, een algemene prijs behaald heeft in al de vorige klassen van de zesde der oude of der nieuwe humaniora, wordt hem door de Regering een bijzondere beloning toegekend. De volgende leerlingen hebben deze beloning verkregen :

VANDOOREN Paul, van de 1ste Latijn-Grieks
DOPERE Frans, van de 1ste Latijn-wiskunde
VRANCKX Arthur, van de 1ste Latijn-wetenschappen

BIJZONDERE BELONINGEN

Door onderstaande verenigingen en firma's werden de volgende bijzondere beloningen toegekend :

De OUDLEERLINGENBÒND EN VRIENDENKRING van het Koninklijk Atheneum verleent een bijzondere beloning aan de leerlingen die het hoogste percentage bereiken, in de vierden voor Nederlands, in de eersten voor aardrijkskunde, in de eerste Latijn-wiskunde voor scheikunde. Deze beloningen worden toegekend aan :

HAPPAERS Christian, van de 4de Latijn-Grieks
LAENEN Christian, van de 4de moderne
VRANCKX Arthur, van de 1ste Latijn-wetenschappen
DOPERE Frans, van de 1ste Latijn-wiskunde

La CRITIQUE BELGE S.A. verleent een bijzondere beloning aan de leerlingen der 1ste Latijn-Grieks, 1ste Latijn-wiskunde, 1ste Latijn-wetenschappen en 1ste wetenschappelijke, die respectievelijk het hoogste aantal punten in de scheikunde, in de wiskunde, in de biologie en in de natuurkunde bekomen.
Deze beloningen worden toegekend aan :

STERCKX Guido, van de 1ste Latijn-Grieks
DOPERE Frans, van de 1ste Latijn-wiskunde
VRANCKX Arthur, van de 1ste Latijn-wetenschappen
MINSCHART André, van de 1ste wetenschappelijke

De N.V. GALLIC te Bost verleent een bijzondere beloning aan de leerlingen die het hoogste percentage behaalden in de geschiedenis en in de economische wetenschappen. Deze beloning wordt toegekend aan :

LAENEN Christian, van de 4de moderne
WUYTS Freddy, van de 3de economische

De ALGEMENE SPAAR- EN LIJFRENTEKAS verleent een bijzondere beloning aan de leerlingen, die in de hogere cyclus van de oude en van de moderne humaniora het hoogste percentage voor geschiedenis behalen. Deze beloning wordt toegekend aan :

COECKAERTS Lucien, van de 2de Latijn-wiskunde
WILLEMS Marcel, van de 3de wetenschappelijke

Het KONINKLIJK ATHENEUM verleent een bijzondere prijs van verdienstelijkheid aan :

VRANCKX Arthur, van de 1ste Latijn-wetenschappen

Het KONINKLIJK ATHENEUM verleent een bijzondere prijs aan de leerlingen die het hoogste aantal punten behalen in het Latijn voor de lagere cyclus en in het Grieks voor de hogere cyclus van de oude humaniora. Deze beloningen worden toegekend aan :

DEJAEGER John, van de 6de Latijnse
MOMBAERS Guy, van de 2de Latijn-Grieks

De Suikerfabriek "GRAND-PONT" verleent vier bijzondere prijzen aan de leerlingen die het hoogste aantal punten behalen voor Frans en Engels in de lagere en hogere cyclussen van de middelbare afdeling.
Deze beloningen worden toegekend aan :

WILLEMS Marcel, van de 3de wetenschappelijke
MINSCHART Michel, van de 5de moderne
WILLEMS Marcel, van de 3de wetenschappelijke
DELORGE Julien, van de 5de Latijnse

De Heer D. DILLEN, opticien, verleent vier bijzondere prijzen aan de leerlingen die het hoogste aantal punten behalen voor biologie en fysica in de lagere en hogere cyclussen van de middelbare afdeling. Deze beloningen worden toegekend aan :

AERTSENS Walter, van de 3de Latijn-wetenschappen
APPELS Yvo, van de 6de Latijnse
VANDOOREN Paul, van de 1ste Latijn-wetenschappen
DELORGE Julien, van de 5de Latijnse

De firma "JUPO-CARS" verleent drie bijzondere prijzen aan de leerlingen die het hoogste aantal punten behalen in de aardrijkskunde voor de voorbereidende afdeling, de lagere en de hogere cyclussen van de mild delbare afdeling

PREVOT Eric, van de 2de Latijn-wiskunde
DELORGE Julien, van de 5de Latijnse
SEVENANTS Patrick, van de 6de voorbereidende afdeling A.

De ROTARY CLUB VAN TIENEN kent een bijzondere beloning toe aan de leerlingen die het hoogste percentage behalen voor het Duits en het Engels in de eersten. Deze beloning wordt toegekend aan :

VAN DOOREN Paul, van de 1ste Latijn-Grieks
TRUYENS Jean, van de 1ste economische.

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YC: That was until the age of 18, and then you moved to Leuven to attend the university?

PVD: I went to Leuven but I decided to enroll in engineering and for that I needed to do a special introductory year because my education in mathematics was not sufficient. This was one whole year of mathematics only, in order to prepare for the entrance exam. That year, I really started to like mathematics. I was 19.

KU LEUVEN

YC: Was Patrick Dewilde your only supervisor?

PVD: In the beginning, I was planning to do my PhD with Piessens, but he had too many students and he suggested that I would choose another supervisor. Patrick Dewilde was just appointed in Leuven as a professor. He was actually an electrical engineer but was teaching a course in numerical linear algebra, and I was doing the homeworks and exercises for that course. So I became his teaching assistant, and then I started to do my PhD with him as well. He gave me a very nice topic which is still not solved. It is the problem of finding prime factors of polynomial matrices. It is still not known what the solutions are. But it was a challenging problem and it raised a lot of related questions.

KU LEUVEN

IEEE TRANSACTIONS ON AUTOMATIC CONTROL, VOL. AC-26, NO. 1, FEBRUARY 1981

The Generalized Eigenstructure Problem in Linear System Theory

PAUL M. VAN DOOREN, MEMBER, IEEE



Paul M. Van Dooren (S'79–M'80) was born in Tienen, Belgium, on November 5, 1950. He received the engineering degree in computer science and the doctorate degree in applied sciences, both from the Katholieke Universiteit, Leuven, Belgium, in 1974 and 1979, respectively.

From 1974 to 1977 he was Assistant at the Division of Applied Mathematics and Computer Science of the Katholieke Universiteit of Leuven. He was a Research Associate at the Department of Electrical Engineering, University of Southern California in 1978–1979 and a Postdoctoral Scholar at the Departments of Electrical Engineering and Computer Science, Stanford University, in 1979–1980. He is currently with the Philips Research Laboratory, Brussels, Belgium. His main interests lie in the areas of numerical analysis and linear system theory.

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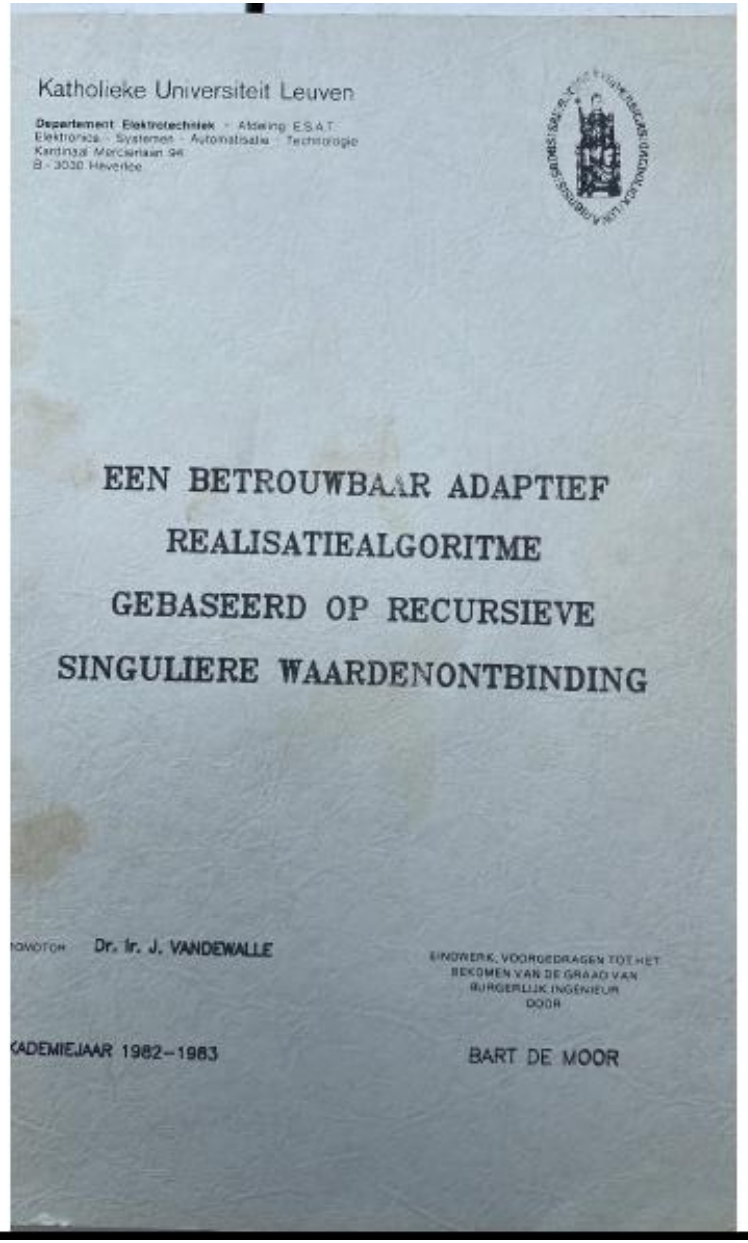

Katholieke Universiteit Leuven

Departement Elektrotechniek - Afdeling E.S.A.T.
Elektronica - Systemen - Automatisatie - Technologie
Kardinaal Mercierlaan 94
B - 3030 Heverlee

EEN BETROUWBAAR ADAPTIEF
REALISATIEALGORITME
GEBASEERD OP RECURSIEVE
SINGULIERE WAARDENONTBINDING

promotor Dr. ir. J. VANDEWALLE

EINDWERK, VOORGEDRAGEN TOT HET
BEKOMEN VAN DE GRAAD VAN
BURGERLIJK INGENIEUR
DOOR

BART DE MOOR

KADEMIEJAAR 1982-1983





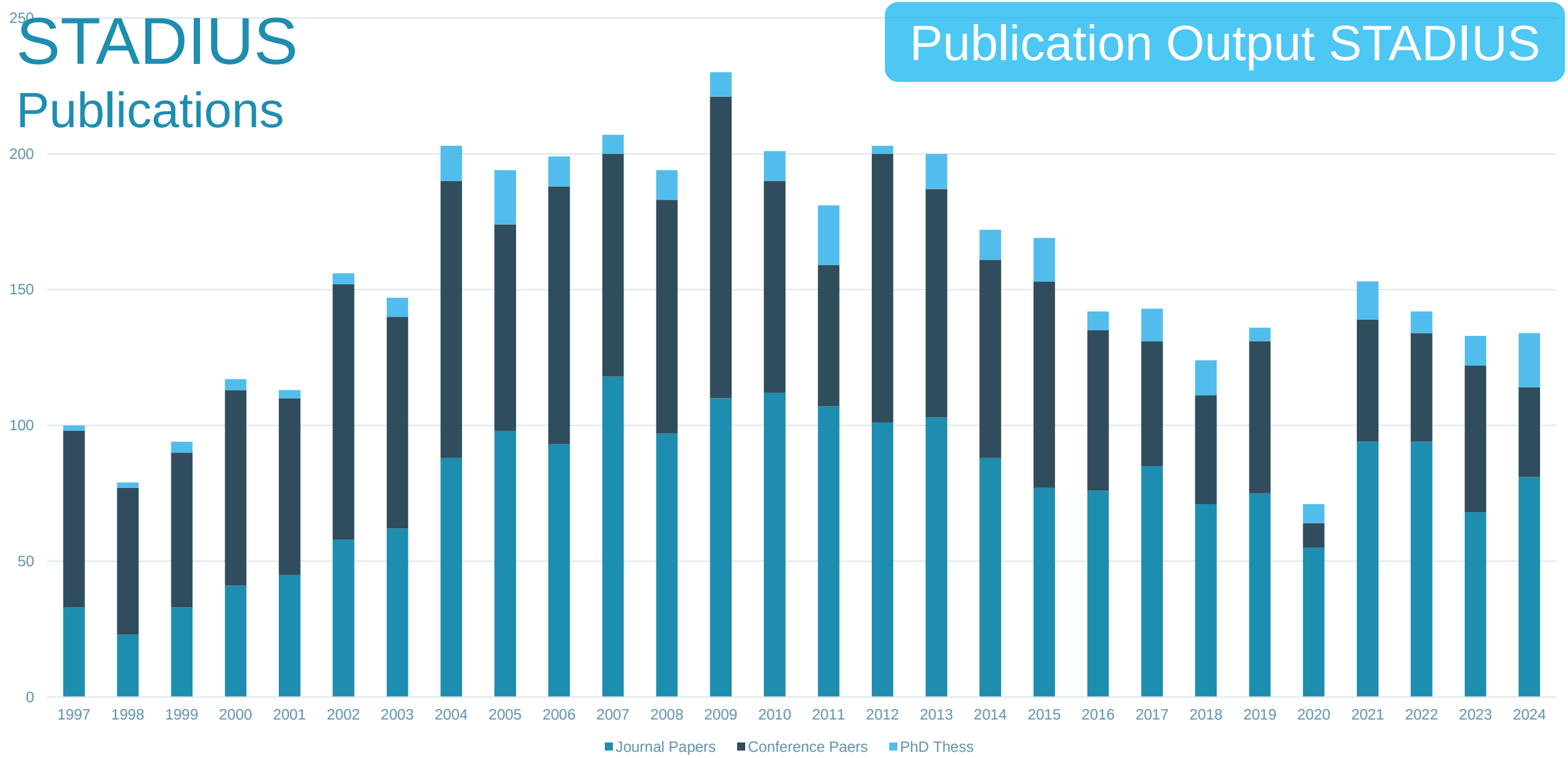


KU LEUVEN

STADIUS

Publications

Publication Output STADIUS



KU LEUVEN



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Promotors : S. Van Huffel and P. Van Dooren

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KU LEUVEN

Liege
1997



PVD: That was a NATO ASI workshop held in Leuven, a special event that I organized in 1988. Actually Gene Golub suggested that we should have a workshop in Belgium on numerical linear algebra, signal processing and parallel algorithms.

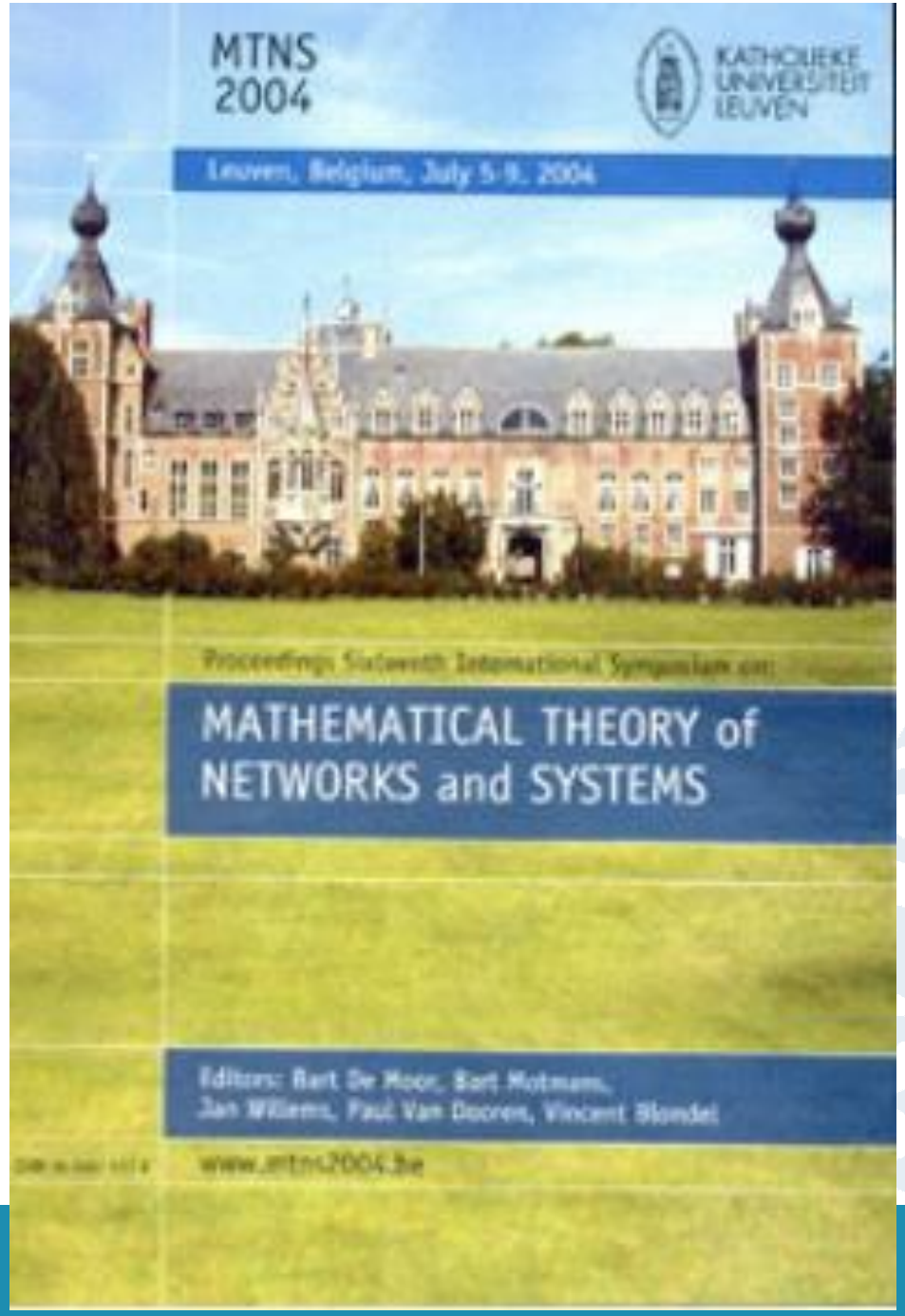
YC: It was organized only once?

PVD: This was organized only once, but then afterwards there were other meetings on SVD and Total Least Squares applications. They were organized by Bart De Moor, Marc Moonen, Sabine Van Huffel and Joos Vandewalle. Leuven became a popular place for meetings.

YC: What was the form of that meeting?

PVD: It was a two week meeting on invitation only. There were about 90 to100 people. It was a very nice meeting. I still have pictures of that. Sven Hammarling and Gene Golub delivered me the Order of the Shiny Red Hat (which was a carnival hat) and a Charter which was signed by everybody. It was for fun, of course, but it was a nice attention. You will not find the Order of the Shiny Red Hat in my CV.

KU LEUVEN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Editors: Bart De Moor, Bart Motmans,
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KU LEUVEN



YC: I remember that you have a funny story in your family, what was that again?

PVD: Oh yeah, you are talking about my grandfather and my wife's uncle. During the second World War, my wife's uncle was blowing up bridges in Belgium to stop the invasion, and it turned out that my grandfather had helped building these bridges before the war. We found out about this when our families met for the first time. That was a good way to start a good relationship. But, properly speaking, I did not know my grandfather well; he died when I was very young.

KU LEUVEN





KU LEUVEN









KU LEUVEN

CM

Cleve Moler

7 May 2008 at 20:13

Visit to Belgium

Details

To: Bart De Moor, Cc: Patsy Moler

Hi, Bart –

As you already know, I am coming to visit you in a couple of weeks. Alex Meyer from our office in Munich has been making the arrangements. We will fly to Brussels from Lyon on Friday morning, drive to Leuven, give a talk Friday afternoon, and have a MathWorks sponsored dinner Friday evening at your faculty club. Alex tells me that you suggested the guest list for the dinner. Paul Van Dooren is not on the list. Will he be in town? Should we add him to the list?

In addition to the MathWorks scheduled events, I plan to spend the weekend in Brussels. My wife, Patsy, will be flying from Santa Fe to Brussels over Friday night, and joining me Saturday morning for the second week of the lecture tour, and then the Householder meeting in Berlin.

Are you familiar with the restaurant Hof ter Eyecken in Ninove? Patsy and I met the owners in Italy last summer and are thinking of going there for dinner on Sunday night. Is it a good place? Would you and your wife be able to join us? This will be more of a personal social occasion than the Friday night dinner. I will also invite the Van Doorens, if they are available.

I look forward to our visit and, especially, to seeing you on your own turf.

-- Cleve

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LELAND STANFORD JUNIOR UNIVERSITY
DIE LUFT DER FREIHEIT WEHT
1891






GENE H. GOLUB · CHARLES F. VAN LOAN
MATRIX
COMPUTATIONS


CAMRY
V6 LE
PROF SVD



Years after the seminal work on the SVD, Paul Van Dooren was at Stanford and was scheduled to give a talk. In the audience were Wilkinson, Dahlquist, and Gene. At some point during the talk Paul asked, a little nervously: "Do you know what the SVD is?" The immediate answer came: "You are at the SVD Headquarters!"

"And everytime you use it, we will tax you !"

YC: What about Bart de Moor?

PVD: I knew him from Leuven, but got to know him better in Stanford. The Stanford connection started with Patrick Dewilde : he was at Berkeley but visited Stanford quite often. He introduced me to Tom Kailath and Gene Golub. Both of them got interested in the students graduating from Leuven. After that, Bart de Moor, Sabine Van Huffel and Marc Moonen, all visited Stanford for some time.

As he liked to say, “Every numerical analyst has a second home at Stanford”.

Nick Trefethen in Obituary Gene Golub in Nature








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Thomas Kailath



Voor de Gevers....



Jan Willems

YC: You received the SIAM Wilkinson prize in Numerical Analysis and Scientific Computing in 1989. What is this prize?

PVD: This was for the contributions to a particular area of scientific computing during the last 4 years. It is a quadrennial prize. Gene was on the committee and probably had an impact on the decision. I received the prize for my work on the interaction between linear algebra and systems and control theory. That topic was quite novel in those days. Alan Laub, Bruce Moore, myself and few others, were the pioneers of that area, in a sense.

YC: Who nominated you for that prize?

PVD: I do not know, but probably Gene.

KU LEUVEN



KU LEUVEN

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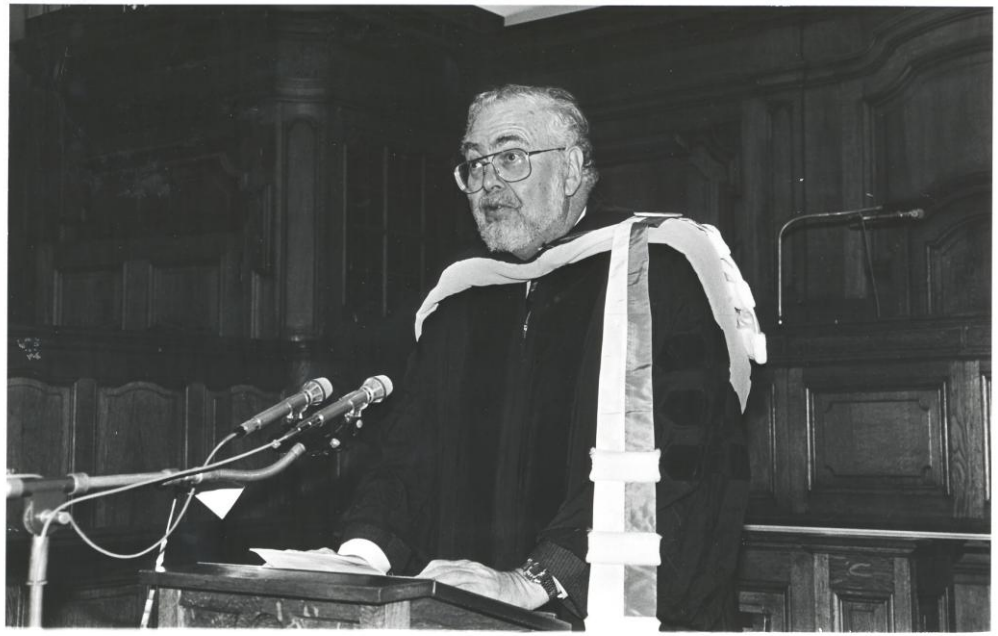
KU LEUVEN









RVTGERVS DILLEMANS, FACVLTATIS IVRIS PROFESSOR ORDINARIVS, IVRIS DOCTOR, LEGVM MAGISTER, PHILOSOPHIAE LICENTIATVS, STVDIORVM VNIVERSITATVM SEVLENSIS KYVNG HEE DICTAE, VVASHINGTONIENSIS CATHOLICAE, OSACANAE KANSAI DICTAE, ITEM COLLEGII LOYOLANI MARYLANDENSIS DOCTOR HONORIS CAVSA, ITERVM RECTOR STVDIORVM VNIVERSITATIS CATHOLICAE LOVANIENSIS IN VRBE LOVANIENSI, OMNIBVS PRAESENTES LITTERAS INSPECTVRIS SALVTEM.

CVM EXIMIVS VIR EVGENIVS H. GOLVB, MATHEMATICORVM DOCTOR, DISCIPLINAE ORDINATORIAE PROFESSOR CATHEDRATICVS A FLETCHER-JONES VOCATVS IN STVDIORVM VNIVERSITATE STANFORDENSI ET PROGRAMMATIS ARTI ORDINATORIAE SCIENTIFICAE FOVENDAE DIRECTOR, DOCTOR TECHNOLOGIAE H.C. STVDIORVM VNIVERSITATIS LINCOPIENSIS, DOCTOR H.C. STVDIORVM VNIVERSITATIS SCIENTIFICAE, TECHNOLOGICAE ET MEDICAE GRATIANOPOLITANAE, ITEM STVDIORVM VNIVERSITATIS VVATERLOENSIS, DOCTOR IVRIS H.C. STVDIORVM VNIVERSITATIS TAODVNENSIS SCOTORVM, DOCTOR SCIENTIARVM H.C. STVDIORVM VNIVERSITATIS ILLINOIDIS, SOCIVS AD HONOREM COLLEGII SANCTAE CATHARINAE OXONIENSIS, ITEM INSTITVTI AMERICANI MACHINATIONIS ELECTRICAE ET ELECTRONICAE, SOCIVS ACADEMIAE NATIONALIS AMERICANAE MACHINATORVM, SOCIVS PEREGRINVS REGIAE ACADEMIAE SVECANAE DISCIPLINARVM MACHINATRICVM, ALGEBRAE LINEARI ET IMPRIMIS VALORIBVS DECOMPONENDIS SINGVLARIBVS INSIGNEM OPERAM CONTVLERIT IDEMQVE AD PERPLEXAS FORMAS RECVRRENTES PHYSICAS OPE NVMERORVM ORDINATRI SIMVLANDAS INVESTIGATOR EXSTITERIT PRINCEPS ;

CVM ET DVOS COMMENTARIOS CONDIDERIT PERIODICOS, QVIBVS VIA MONSTRETVR PROGRESSVS FACIENDI IN DISCIPLINA ORDINATORIA ET MATHEMATICA NVMERORVM ;

NOS PRO POTESTATE NOBIS FACTA ET CONCILIO ACADEMICO NECNON FACVLTATE SCIENTIARVM VSVI ADHIBITARVM ADSENTIENTIBVS EVNDEM EXIMIVM VIRVM

EVGENIVM H. GOLVB

FACVLTATIS SCIENTIARVM VSVI ADHIBITARVM DOCTOREM HONORIS CAVSA CREAVIMVS ET RENVNTIAVIMVS.

CVIVS REI VT FIRMA SIT AC TESTATA FIDES, DIPLOMA HOC PVBLICVM A NOBIS VNA CVM PRAEFECTO REBVS GERENDIS ET DECANO FACVLTATIS SCIENTIARVM VSVI ADHIBITARVM SVBSCRIPTVM ET VNIVERSITATIS SIGILLO CONFIRMATVM DANDVM CVRAVIMVS.

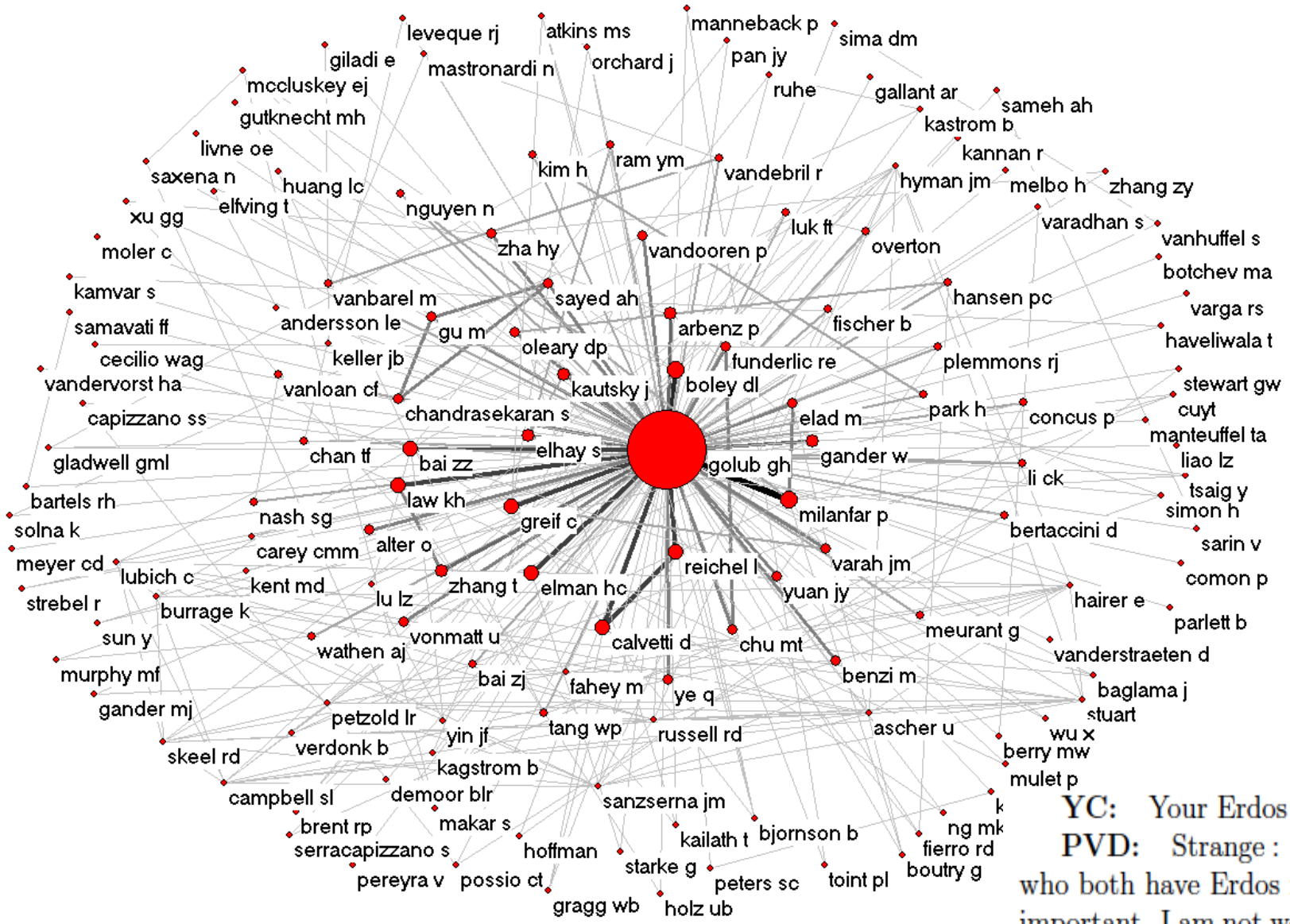
LOVANII, KALENDIS DECEMBRIBVS ANNI M.D.CCCC.XCII.

CAROLVS TAVERNIER
PRAEFECTVS
REBVS GERENDIS

RVTGERVS DILLEMANS
RECTOR

STEPHANVS AERNOVDT
DECANVS
FACVLTATIS SCIENTIARVM VSVI ADHIBITARVM

KU LEUVEN



YC: Your Erdos number is 4, what do you think about this?

PVD: Strange : I am a coauthor of Gene Golub and of Vincent Blondel who both have Erdos number 2, I thought. But, I do not think that this is important. I am not working in an area that Erdos was interested in. I prefer to say that my Golub number or my Wilkinson number is 1.

KU LEUVEN



KU LEUVEN

>
> Dear Friends,
>
> I'm sitting in the basement of a private home in Gambo,
> Newfoundland
> about 30 kilometers from Gander. My flight from London to
> Chicago was
> diverted to Gander. The pilot told us we must land but gave
> no reason
> (though he mentioned the plane was ok). We spent eighteen
> hours
> overnight on the plane with little food though the
> stewardesses were
> very considerate re:my diabetic condition.
>
> At any rate, I am safe and sound in this small town with no
> newspapers
> and very little to do. The setting is very beautiful with
> lovely hills
> and water nearby. The folks here are incredibly nice, giving
> us rides
> and supplying us with food and comfort. And the Salvation
> Army folks
> have been extremely helpul in organizing our stay.
>
> It is not clear how long we'll be staying here. There are
> frequent
> rumors about announcement of departure times but we seldom
> get any
> hard information. Eventually we will depart for Chicago and
> I'll stop
> there for a few days before continuing on to Toronto.
>
> There is not much now that I can add to the events of these
> past few
> days. It's a depressing event in a depressing world.
>
> Best wishes and thanks to those who have written me.
>
> Gene

Hilde Devoghel

Van: Bart De Moor <bart.demoor@esat.kuleuven.ac.be>
Aan: Gene Golub <golub@sccm.Stanford.EDU>
CC: Hilde Devoghel <hilde.devoghel@dsa.kuleuven.ac.be>
Verzonden: vrijdag 21 september 2001 11:53
Onderwerp: Fw: [Fwd: From Newfoundland]

Hi Gene,

Glad to hear that you are safe and well !

Depressing and shocking terrorist acts indeed.
I am also convinced that the world has really changed
after these events !
Let's hope that the future will bring us some wisdom !

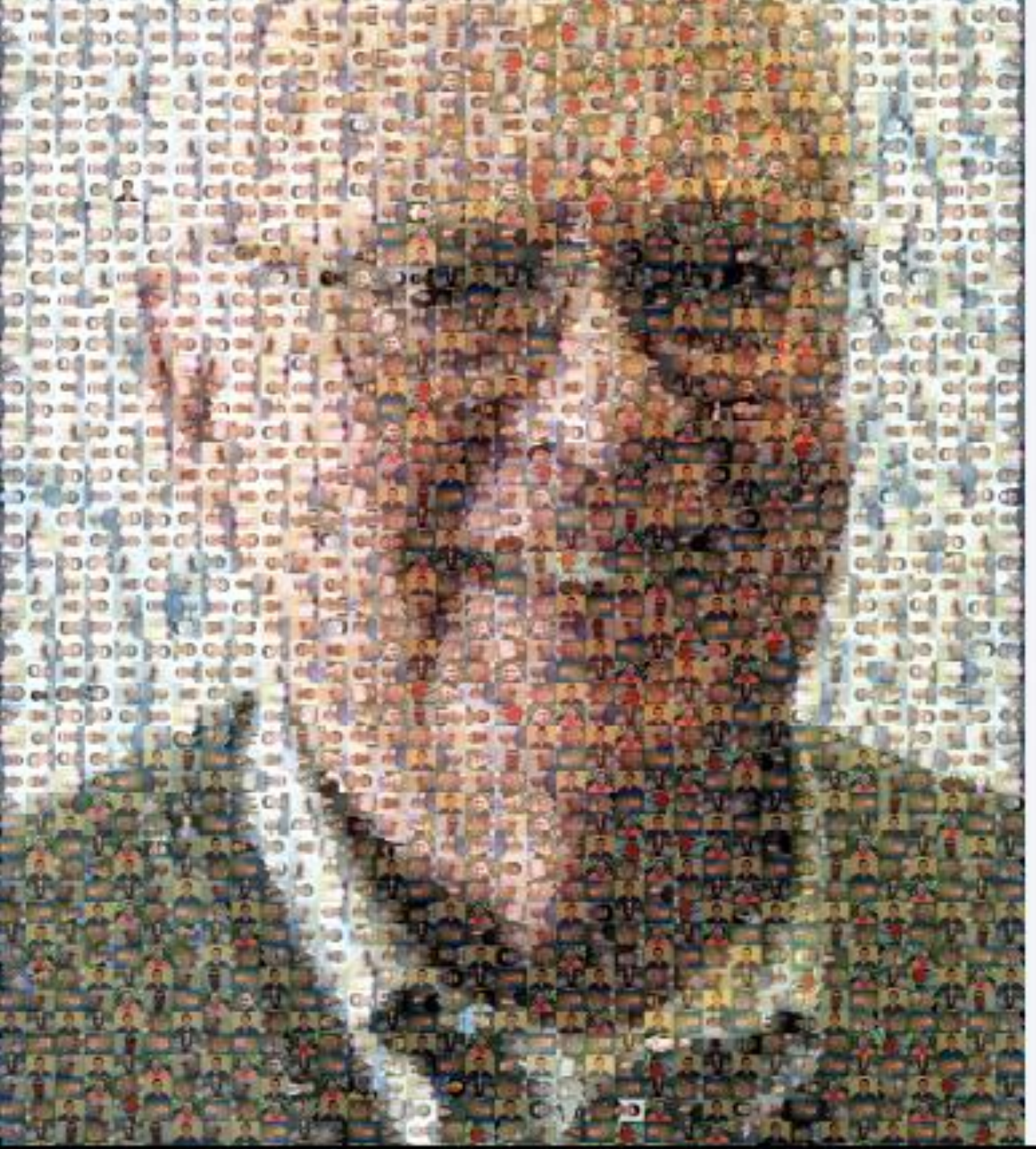
bdm

----- Original Message -----
From: Ida Tassens <Ida.Tassens@esat.kuleuven.ac.be>
To: Bart De Moor <Bart.DeMoor@esat.kuleuven.ac.be>; Sabine Van Huffel
<Sabine.VanHuffel@esat.kuleuven.ac.be>
Sent: dinsdag 18 september 2001 11:19
Subject: [Fwd: From Newfoundland]

>
>
> -------- Original Message --------
> Subject: From Newfoundland
> Date: Tue, 18 Sep 2001 02:15:03 -0700
> From: Gene Golub <golub@sccm.Stanford.EDU>
>
> Update 14 Sept : We are still here! The rumors are that we
> will be leaving
> on Sunday. My phone number here is (709) 674 -5299. Please
> note we are
> 4 1/2 hours earlier than in CA.
> GG.
>
>
>
>
> Gambo, Newfoundland
> 13 Sept 2001

Outline

1. Years in Tienen
2. Years in Leuven
3. Our common network
4. Stanford
5. Working in secrecy and conspiracy
6. **Remembrance Days**
7. Paul, a friend indeed

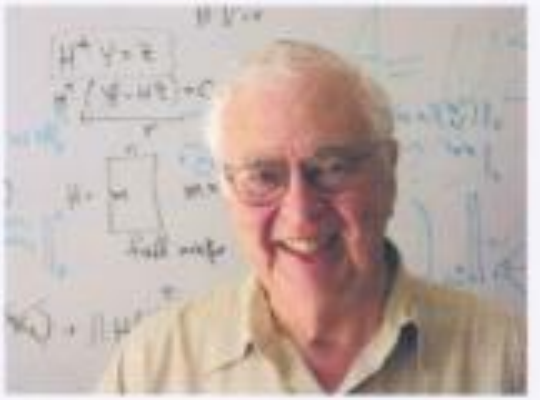


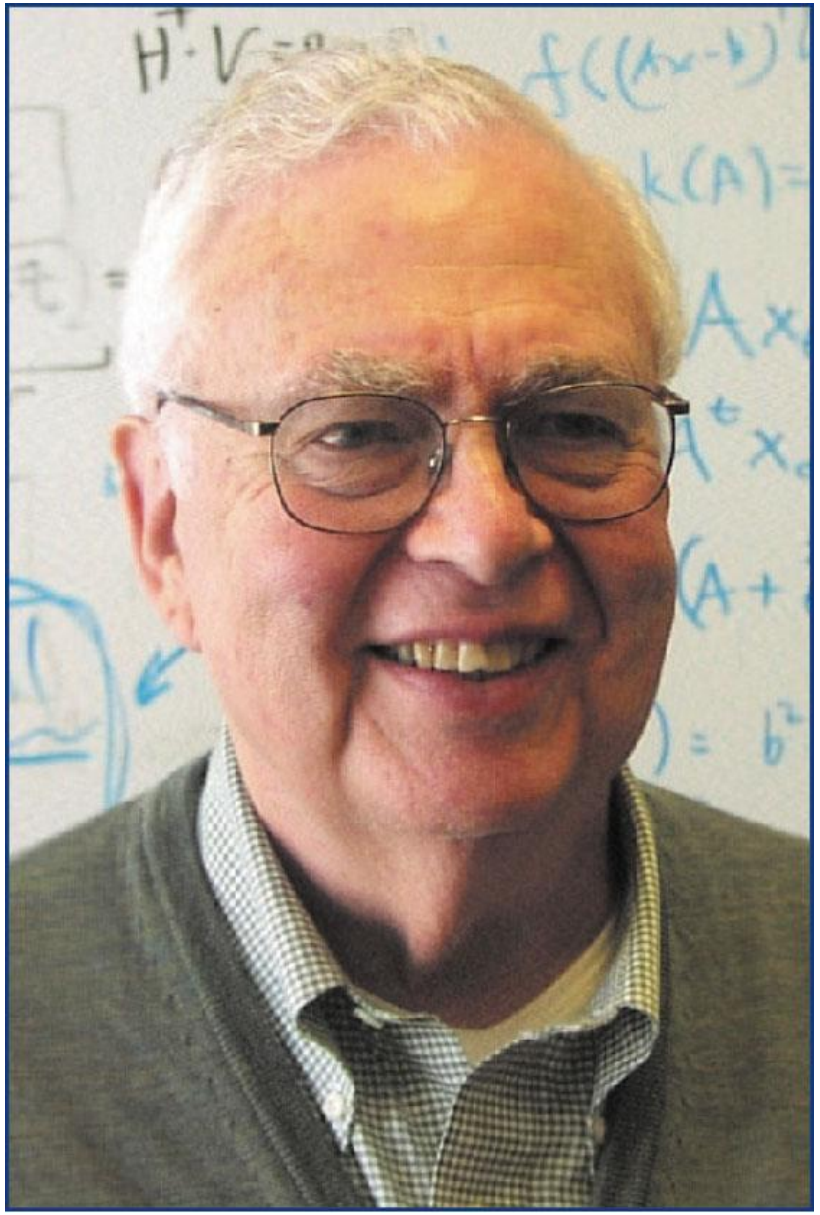
Gene Golub Around the World Commemoration

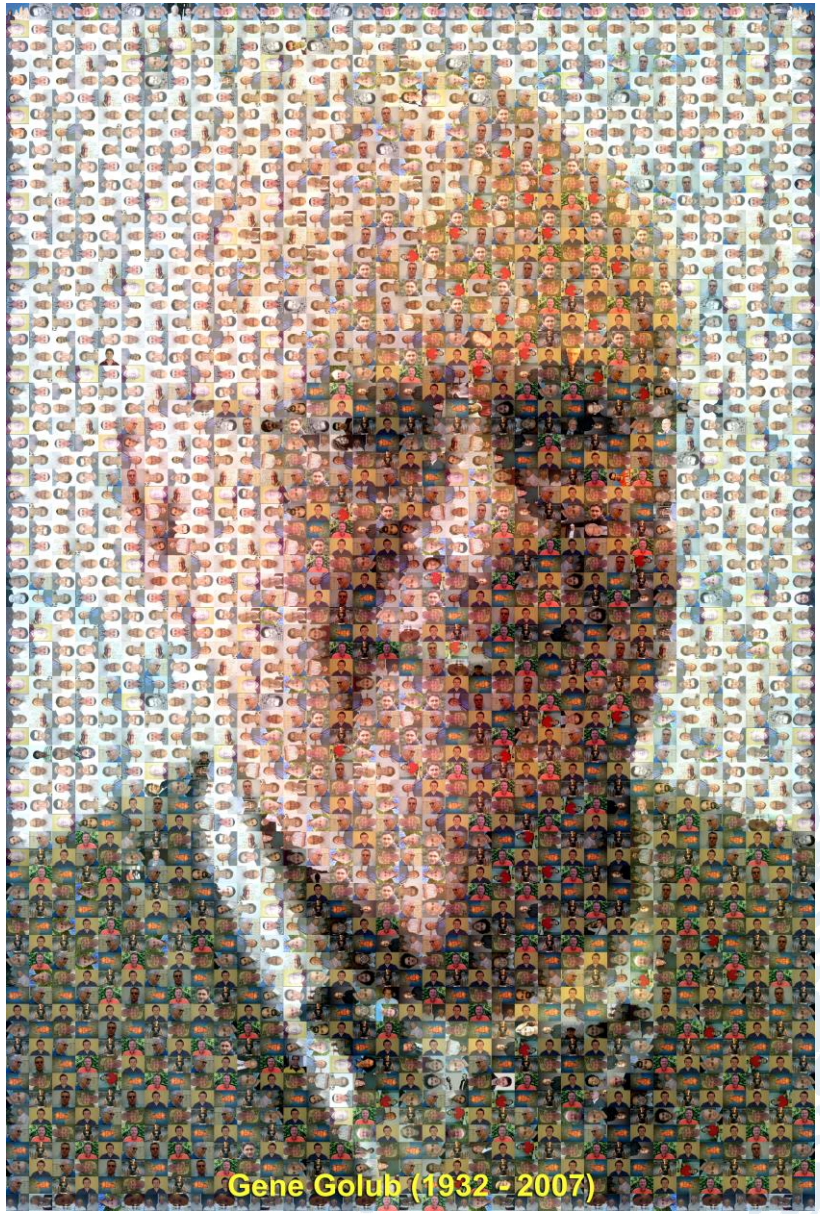
February 29, 2008

K.U.Leuven,
Dept. Electrical Engineering
Leuven, Belgium

B. De Moor, P. Van Dooren,
S. Van Huffel






Gene Golub (1932 - 2007)

Numerical Analysis Around the World



On February 29, the worldwide mathematical/computational sciences community turned out for a well-choreographed celebration of the life and work of Gene Golub, who died on November 16, 2007. Some of the events that unfolded in the course of the day took the form of technical sessions, some had special structures, and at least one inspired a noteworthy graphic. All made space for fond reminiscences. *See page 3.*

KU LEUVEN

9:00: Opening: Bart De Moor, Paul Van Dooren, Sabine Van Huffel

9:30: *G. Alistair Watson,* Univ. Dundee, Div. Mathematics
Some extensions of Gene's work on total least squares

10:00: *Claude Brezinski*, Univ. des Sciences et Technologies de Lille
Errors in the solution of linear systems, with an application to regularization

10:30: *Sabine Van Huffel*, K.U.Leuven, EE Dept. (ESAT/SCD)
Impact of numerical linear algebra in computational biomedical signal processing

11:00: Coffee

11:30: *Paul Van Dooren*, UCL, CESAME
How to improve your PR (in collaboration with C. de Kerchove and L. Ninove)

12:00: *Martin H. Gutknecht*, ETH Zurich, Applied Mathematics
Modified Moments for Indefinite Weight Functions

12:30: *Raf Vandebril*, K.U.Leuven, Dept. of Computer Science
On the A x equals Lambda B x problem

13:00: Lunch + Opportunity for “interview”

14:30: *Bo Kågström*, Umea Univ., Dept. Computing Science
Ill-conditioned eigenvalue problems and canonical forms: a journey with Gene from Jordan to periodic Schur
15:00: *Lieven de Lathauwer*, EE Dept. (ESAT/SCD)
Multilinear generalizations of the Singular Value Decomposition
15:30: *Annie Cuyt*, Univ. Antwerpen, Dept. Mathematics and Computer Science
Gene's beloved "Shape from Moments" problem

16:00: Coffee
16:30: Skype with U. Waterloo and U.Mass, Dartmouth

16:40: *Gregory Boutry*, Univ. Catholique de Lille, Faculte Libre des Sciences et Technologies
Gene from Marrakech to Stanford
17:10: *Bart De Moor,* K.U.Leuven, EE Dept. (ESAT/SCD)
Generalizations of the singular value and the QR decomposition for multiple matrices
17:40: End

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Vol. 12, No. 3, pp. 401–425, July 1991

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THE RESTRICTED SINGULAR VALUE DECOMPOSITION: PROPERTIES AND APPLICATIONS*

BART L. R. DE MOOR† AND GENE H. GOLUB‡

THEOREM 1 (the restricted singular value decomposition). *Every triplet of matrices* A $(m \times n)$, B $(m \times p)$, *and* C $(q \times n)$ *can be factorized as*

$$A = P^{-*} S_a Q^{-1},$$
$$B = P^{-*} S_b V_b^{*},$$
$$C = U_c S_c Q^{-1},$$

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SIAM J. MATRIX ANAL. APPL.
Vol. 13, No. 4, pp. 993–1014, October 1992
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GENERALIZATIONS OF THE SINGULAR VALUE AND QR DECOMPOSITIONS*

BART DE MOOR† AND PAUL VAN DOOREN‡

We dedicate this paper to Gene Golub, a true source of inspiration for our work, but also a genuine friend, on the occasion of his 60th birthday

THEOREM 4.1 (generalized singular value decompositions for k matrices). *Consider a set of k matrices with compatible dimensions: $A_1\ (n_0 \times n_1), A_2\ (n_1 \times n_2), \ldots, A_{k-1}\ (n_{k-2} \times n_{k-1}), A_k\ (n_{k-1} \times n_k)$. Then there exist*

—*Unitary matrices $U_1\ (n_0 \times n_0)$ and $V_k\ (n_k \times n_k)$.*
—*Matrices $D_j, j = 1, 2, \ldots, (k-1)$ of the form*







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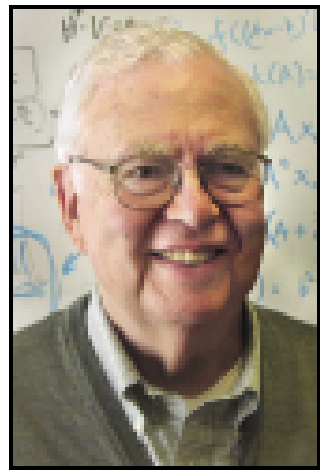
Professor Bart De Moor over Gene H. Golub

Wereldwijde herdenking grondlegger lineaire algebra

Op 16 november van vorig jaar overleed Gene H. Golub, een klinkende naam in de numerieke lineaire algebra en auteur van een klassieker binnen zijn vakgebied. Hij was vooral ook vriend en inspirator van velen. Zij zijn het die hem binnenkort herdenken met een wereldwijde Gene Golub Around the World Commemoration, die gelijktijdig gehouden wordt op vijfentwintig plaatsen verspreid over de continenten. Het evenement vindt plaats op 29 februari, de dag dat Gene Golub 'negentien' jaar zou geworden zijn. Organisator in Leuven is professor Bart De Moor van het Departement Elektrotechniek, ESAT, Afdeling SCD.

Luk Vanraepaille



(© KU Leuven)

De Moor: "Het was schrikken voor iedereen die Golub kende en dat zijn er nogal wat. Hij reisde nog conferentiënd de wereld rond om overal zijn wetenschappelijke kinderen en kleinkinderen te bezoeken. Tussen twee reizen door is een acute vorm van leukemie bij hem vastgesteld, die hem geveld heeft nog voor met de chemotherapie kon gestart worden. Vrienden hebben niet veel de tijd gehad om de verworvenheden die hij was in het ziekenhuis aan een computer te helpen."

De naam Golub was ook academisch een grote stijlgever. Hij is geboren in Chicago in een joods gezin van Letse Oekraïense migranten. Hij studeerde er wiskunde aan de universiteit van Illinois. Zijn relaties – toen al – brachten hem later naar het prestigieuze Stanford, gevolgd door al wat andere disciplines met een praktische toepassingen, de lineaire algebra, vertaald naar de wereld van het digitale. In wezen doen computers niets anders dan eindeloos reeksen van bewerkingen maken, die vroeger trouwens gewoon door mensen, manueel vroeger, verricht werden. De truuk van Golub begon met zijn interesse te doen, waardoor de formules wel van Moore in gang gezet werd, die stelt dat het aantal transistors op een computerchip om het anderhalf jaar zou verdubbelen.

> "Jammer genoeg worden algoritmen wetteliijk gezien ontdekt en niet uitgevonden. Ze zijn dus helaas niet patenteerbaar, hoewel ze soms wel degelijk een grote economische waarde hebben."

Daarmee wordt bedoeld dat de afhandelingsalgoritmen die ook een computer maakt, niet doorwegen op het resultaat van zijn berekeningen. Op zich zijn die finesses minieme maar als zo'n ding miljarden berekeningen maakt, kan ook een kleine afwijking het eindresultaat compleet compromitteren.

"Nu is het jammer genoeg zo dat algoritmen wettelijk gezien ontdekt worden en niet uitgevonden. Ze zijn dus helaas niet patenteerbaar, anders was hij schatrijk geworden. Hij was wetteliijk één van de rijkste mensen. Zijn technologie zit overal, maar onderliggend, als een bouwsteen ontdekt. Dat is de enige reden dat hij niet ook bij het grote publiek een klinkende naam is geworden."

Delft

De Moor werkte als postdoc twee jaar in Stanford en ging daarna naar Berkeley. Daar ontmoette hij Golub, toen hij weer even op reis was en zijn huis dicht bij hem stond.

"Hij vloog de wereld rond, inderdaad. Zijn naam als overlegen 'duif' betekende, 'columbus' in het Latijn, dus. Hij verbleef ook geregeld voor langere periodes in Leuven en dan nam hij graag zijn intrek in het Begijnhof, waar hij naar eigen zeggen de laatste beetjes rust vond. Maar wat ik daar van moest geloven, weet ik niet zo goed. Hij maakte wel veiler grapjes."

In 1991 heeft hij van onze universiteit een eredoctoraat gekregen. Het was het jaar dat hij zestig werd. Ik herinner me dat hij een beetje gaf rond de tijd dat de bekroning viel. Omdat mijn vrouw

KU LEUVEN

Remembering Gene Golub Around the World on February 29

By Michael L. Overton

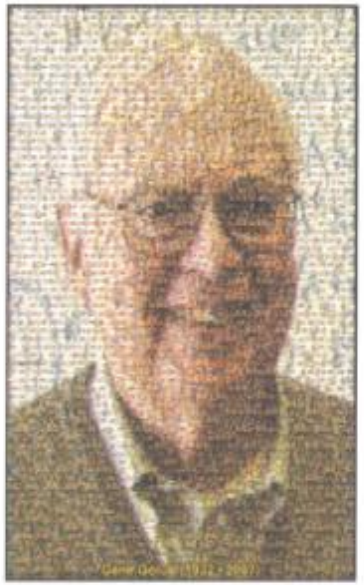
Gene H. Golub was born in Chicago on February 29, 1932, and died at Stanford on November 16, 2007, sending a wave of shock and sorrow around the world. Gene's impact on numerical analysis and linear algebra was huge, as evident in his recently published selected works, *Milestones in Matrix Computation*.* The book's five sections describe Gene's contributions to iterative methods, least squares problems, matrix factorizations, orthogonal polynomials and quadrature, and eigenvalue problems, with commentaries from leading experts in each area.

But Gene's fundamental scientific contributions account only in part for his enormous impact. Beyond the many important roles he played within our community (including a term as SIAM president), he was truly an ambassador-at-large for scientific computing, never tiring of discovering new applications and problems and promoting algorithms for their solution. His interest in people also played a large part, as made clear by the blog set up soon after his death (http://genehgolub.blogspot.com). Gene loved to help people, particularly young scientists just starting their careers. His hospitality at Stanford was legendary. Numerical analysts from all over the world became a big extended family for Gene, and he welcomed them all to Stanford with great warmth, no matter how young or old, famous or not, for days or weeks or months. He loved to travel and he visited this extended family everywhere. The year 2007 was no exception—he spent five months of the spring and summer based at Oxford, and in October he went to Venezuela and France to help celebrate two birthdays, Victor Pereyra's 70th and Gerard Meurant's 60th. He had just returned to Stanford from China

ing gift presented to him at the banquet—at a time when cell phones were a novelty. It turned out to be Bart De Moor calling from Leuven to inform Gene that he would be awarded his sixth honorary degree in June.) Parties seemed to be almost as frequent in non-leap years, perhaps to make up for Gene having no birthday in those years. The biggest of these was held just over a year ago: the "Stanford 50, Golub 75" meeting—50 years of numerical analysis at Stanford, dating from the arrival of George Forsythe, and 75 years since Gene's birth. I was one of the organizers and, like the more than 250 people who attended, am so glad now that we held the meeting. All kinds of nice things were said about Gene at a banquet in his honor, and he loved every moment of it.

Soon after Gene's death, several people realized that the most appropriate day to mourn his passing and celebrate his life would be February 29, 2008. And because most of his friends could not go to Stanford, it seemed only natural to hold celebrations of Gene around the globe. The idea quickly gathered momentum. Well over 1000 people participated in 32 events in 23 countries on all six populated continents. As far as I know, not even Gene had contacts in Antarctica.

Appropriately, the biggest celebration was at Stanford, where Gene's colleagues organized a memorial program for the afternoon of February 29, Remembrances in Celebration of Gene Golub. With about 250 people in attendance, all seats and standing room were occupied. Gene's brother and many friends, from as far away as Switzerland, gave tributes, in some cases musical. The memorial was followed the next day by a technical program, Symposium on Gene Golub's Legacy: Matrix Computations—Foundation and Future,



Using photos of participants from all around the world, the organizers of the Leuven meeting assembled a mosaic picture.

Gene. In Toulouse, all the speakers were graduate students. On sabbatical in Italy at the time, I attended the meeting in Pisa. All the other participants were Italian, but everyone spoke English because I was there. I was a little embarrassed until it occurred to me that it would have been the same if Gene had been there in my place—and the Italians welcomed me as warmly as if he were.

A meeting in Tel Aviv was especially appropriate, as Gene's Jewish heritage was important to him. Students and the singular value decomposition—two of Gene's favorite themes—were the focus of a meeting in Kharagpur, India, where people had warm memories of Gene's visit in January

materials posted include programs, pictures, information about the organizers (all of whom deserve many thanks), a video recording from Stanford, and a mosaic picture of Gene, made up of photos of attendees all around the world, assembled by the organizers of the Leuven meeting. Also on the site are links to obituaries of Gene from the *CAIMS Newsletter*, *Linear Algebra and Its Applications*, *Nature*, *The New York Times*, and *SIAM News*, as well as to special issues of *ETNA* and *Numerical Algorithms* that will be published in his honor.

Gene Golub was a complex man. He was raised primarily by his mother, in a classic immigrant success story. He was single most of his life; his four-year marriage in the late 1990s brought him great happiness followed by bitter disappointment. The tragic deaths of his beloved niece and nephew hit him hard, leaving only his brother and sister-in-law and their granddaughter in his immediate family. He could be demanding, easily taking offense when none was intended, and offending others without realizing he was doing so. Despite his achievements and recognition, he often felt insecure, and said so. Yet he loved life, and was enormously grateful for all that it had given him. He was interested in everything, was a voracious reader, and had a great sense of fun. His kindness and generosity knew no bounds. He loved his extended family around the world, and they loved him back, and were glad to show it on February 29. Their tributes to Gene touched as much on what he meant as a friend and mentor as on his scientific achievements, in many cases describing life-changing decisions based on Gene's encouragement. Speaking for myself, Gene has surely had more influence on my life

OBITUARY

Gene H. Golub (1932–2007)

Mathematician and godfather of numerical analysis.

A century ago, matrices and the techniques for their manipulation — linear algebra — were a backwater of mathematics. Today, they are the foundation not just of the mathematical field of numerical analysis, but also of computational science and engineering, and have become indispensable for anyone who wants to get numerical results from a computer. The pre-eminent figure in matrix computations over the past 50 years, Gene Golub, died on 16 November.

Golub was born in Chicago on 29 February 1932, to Jewish parents from Latvia and the Ukraine. His childhood was not affluent, but he was a good student. After two years at a junior college, he transferred to the University of Illinois at Urbana-Champaign, achieving his doctorate there in 1959. At the time, Illinois, with the first of its 'ILLIAC' supercomputers, was a great centre of computing, and Golub showed his affection for his Alma Mater by endowing a chair there 50 years later. Rumour has it that the funds for the gift came from Google stock acquired in exchange for some advice on linear algebra. Google's PageRank search technology starts from a matrix computation — an eigenvalue problem with dimensions in the billions. Hardly surprising, Golub would have said: everything is linear algebra.

He came to believe that in his twenties, as he realized that new methods of orthogonal-matrix factorization introduced by Wallace Givens and Alston Householder offered the right mathematical recipe for solving all kinds of problems. In particular, Golub focused on the idea known as singular value decomposition, SVD, which systematically isolates the dominant components of a linear process. Together with William Kahan and Christian Reinsch, he invented the now-standard SVD algorithms, and showed scientists, engineers and statisticians how these algorithms could be used in areas such as the least-squares method to find the best fit to a curve; in optimization problems and control theory; and for the determination of crucial matrix parameters such as their norms, ranks and condition numbers. In later years he drove a car with the licence plate 'PROF SVD'.

Golub found his way to Stanford University in 1962, eventually becoming the senior professor in its formidable computer science department. In 45 productive years there, he advanced matrix computations in areas as diverse as geodesy, data mining and quantum chromodynamics. The dimension of what was considered a 'big' matrix grew from 100 to 1,000,000 in the same period, and Golub was among the first to develop the iterative algorithms that make problems involving such huge matrices tractable.

As the new methods came in, older ideas such as gaussian elimination (essentially, the way one is taught to solve a system of simultaneous equations in school, by eliminating the variables one by one) became a smaller part of a new and greater enterprise. Along with the new algorithms came a new world of software for solving mathematical problems, such as EISPACK, LAPACK and MATLAB. Golub's book *Matrix Computations*, co-authored with Charles Van Loan of Cornell University, became a bestseller and the definitive textbook of the field. Honours flowed in, including membership of the US National Academies.

As a servant of the wider scientific community, Golub did as much as anybody to make the Society for Industrial and Applied Mathematics (SIAM) the organization it is today. He served it in various capacities, among them as president (1985–87). He also founded and edited two of the society's journals, the *SIAM Journal on Scientific and Statistical Computing* and *SIAM Journal on Matrix Analysis and Applications*. It was his proposal that led to the quadrennial International Congresses on Industrial and Applied Mathematics.

But this impressive list of achievements misses the truly extraordinary aspect of this complex man: the scale of his devotion to people. Golub was a bachelor for most of his life, and his colleagues were his family. No family ever had a more loving, attentive or exasperating father. As he liked to say, "Every numerical analyst has a second home at Stanford". Countless colleagues enjoyed a glass of wine at his home there, and hundreds of them stayed over for a night or even a month at his invitation. How did he remember all our birthdays and reading tastes and children's names?

Golub could not spend a day without other people. He would eat dinner with them, talk matrices with them, organize conferences with them, write papers and books with them, argue academic politics with them — an endless dance of interactions, plans and projects. Anywhere in the world, a numerical analyst knows who is meant by 'Gene'. About 250 of them were his co-authors. They knew that it would fall to them to do most of the writing; but Golub saw the connections, knew the literature, and made the paper happen.



He seemed almost to have invented e-mail. As early as 1981, his office computer was set up to beep the moment a message arrived. His personal address list evolved into the worldwide database of numerical analysts, and his notes to friends became the Numerical Analysis Digest. This newsletter, one of the first e-bulletins, is now sent to some 8,000 recipients weekly. He could not sit still. As he left us in Oxford last September after an extended sabbatical visit, having spent much of the preceding months talking with the graduate students in the common room — to which he had donated $1,000 for a biscuit fund — he mentioned that he had three trips to China planned for the upcoming year.

Gene Golub was restless and never entirely happy. He was a demanding friend; behind his back, we all had Gene stories to tell. It was a huge back: Gene was big, dominating any room he was in, and grew more impressive and imposing with the years. Graduate students around the world admired and loved him, and he bought them all dinner when he got the chance. His unexpected death, in Stanford in between speaking at a conference in Hong Kong and flying to Zurich for his eleventh honorary degree, has left the world of numerical analysis orphaned and reverberating.

Lloyd N. Trefethen
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e-mail: lnt@comlab.ox.ac.uk

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KU LEUVEN

Outline

1. Years in Tienen
2. Years in Leuven
3. Our common network
4. Stanford
5. Working in secrecy and conspiracy
6. Remembrance Days
7. **Paul, a friend indeed**





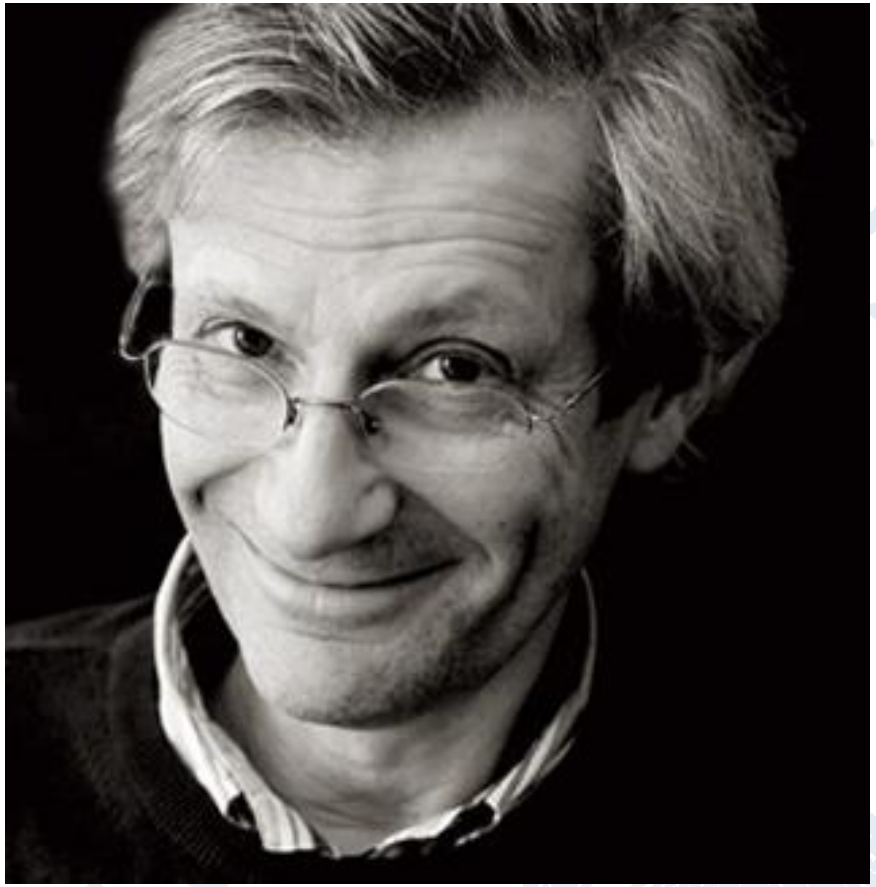




Paul,

Thanks for everything !!

Ad multos annos



Be aware !
Matrices are everywhere !