



**2011 International Conference on  
Advanced Computer Science and Information Systems  
(Proceedings)**

Mercure Convention Centre, Jakarta  
December 17<sup>th</sup>-18<sup>th</sup>, 2011

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Faculty of Computer Science  
Universitas Indonesia

## Welcome Message from General Chairs



On behalf of the Organizing Committee of this International Conference on Advanced Computer Science and Information Systems 2011 (ICAC SIS 2011), we would like to extend our warm welcome to all of the presenter and participants, and in particular, we would like to express our sincere gratitude to our plenary and invited speakers.

This international conference is organized by the Faculty of Computer Science, Universitas Indonesia, and is intended to be the first step towards a top class conference on Computer Science and Information Systems. We believe that this international conference will give opportunities for sharing and exchanging original research ideas and opinions, gaining inspiration for future research, and broadening knowledge about various fields in advanced computer science and information systems, amongst members of Indonesian research communities, together with researchers from Germany, United Kingdom, Rusia, Australia, Japan, South Korea, Malaysia, Thailand, Vietnam and other countries.

This conference focuses on the development of computer science and information systems. Along with 5 plenary and 3 invited speeches, the proceedings of this conference contains 66 papers which have been selected from a total of 134 papers from fourteen different countries. These selected papers will be presented during the conference.

We also want to express our sincere appreciation to the members of the Program Committee for their critical review of the submitted papers, as well as the Organizing Committee for the time and energy they have devoted to editing the proceedings and arranging the logistics of holding this conference. We would also like to give appreciation to the authors who have submitted their excellent works to this conference. Last but not least, we would like to extend our gratitude to the Ministry of Education of the Republic of Indonesia, the Rector of Universitas Indonesia, and the Dean of the Faculty of Computer Science for their continued support towards the the ICAC SIS 2011 conference.

Sincerely yours,  
**General Chairs**  
**Ito Wasito**



## Welcome Message from the Dean of Faculty of Computer Science, Universitas Indonesia



On behalf of all the academic staff and students of the Faculty of Computer Science, Universitas Indonesia, I would like to extend our warmest welcome to all the participants to the Mercure Convention Centre in Ancol, Jakarta on the occasion of the 2011 International Conference on Advanced Computer Science and Information Systems (ICACSYS).

Just like the previous two events in this series (2009 in Depok and 2010 in Bali), I am confident that ICASIS 2011 will play an important role in encouraging activities in research and development of computer science and information technology in Indonesia, and give an excellent opportunity to forge collaborations between research institutions both within the country and with international partners. The broad scope of this event, which includes both theoretical aspects of computer science and practical, applied experience of developing information systems, provides a unique meeting ground for researchers spanning the whole spectrum of our discipline. I hope that over the next two days, some fruitful collaborations can be established.

I also hope that the special attention devoted this year to the field of pervasive computing, including the very exciting area of wireless sensor networks, will ignite the development of applications in this area to address the various needs of Indonesia's development.

I would like to express my sincere gratitude to the distinguished invited speakers for their presence and contributions to the conference. I also thank all the program committee members for their efforts in ensuring a rigorous review process to select high quality papers.

Finally, I sincerely hope that all the participants will benefit from the technical contents of this conference, and wish you a very successful conference and an enjoyable stay in Jakarta.

Sincerely,  
**Professor T. Basaruddin Ph.D**  
**Dean of the Faculty of Computer Science**  
**Universitas Indonesia**



## **Welcome Message from Vice Minister of Education Ministry of Education and Culture of the Republic of Indonesia**



Ladies and Gentlemen, speakers and guests of the 2011 International Conference on Advanced Computer Science and Information Systems, or simply ICACSIS 2011, Good Day, Assalamu'alaikum Wr. Wb.

Allow me to first express my gratitude towards our honorary chairs and our honored speakers from all around the world, who have spared their valuable time to contribute to this conference along with all the other distinguished participants who have assembled here in Jakarta, over the next two days, for academic discussions on advanced computer science and information systems.

In today's information age, it seems that there is no longer an aspect of life that is unaffected by the advances of information and communication technology, or ICT. The Ministry of Education and Culture of the Republic of Indonesia recognizes that ICT has a huge role to play in addressing national issues and is committed to supporting research on how ICT can further solve these problems.

In recognition of the importance of ICT in national development, the Indonesian government's recently unveiled Master Plan for the Acceleration and Expansion of Indonesia's Economic Development (MP3EI) includes ICT as a crucial component of its 22 primary activities. This master plan is a bold initiative which aims to make Indonesia one of the world's 10 biggest economies by 2025, taking GDP to \$4.5 trillion and increasing the per capita income from \$3000 now to \$15,000. One of the strategic initiatives of this Master Plan is to encourage large scale ICT investment, including the provision of essential infrastructure such as affordable and usable broadband throughout the archipelago.

Such initiatives will be expected to serve as an enabling technology, and the government sees the national education sector – particularly higher education – as one of the catalysts to leverage this technology to directly impact Indonesia's national competitiveness. To that end, the Ministry encourages researchers and academics to improve national competitiveness through outstanding research achievements in the field of ICT. There are many research areas which can improve Indonesia's competitiveness, ranging from e-Government solutions that improve efficiency and effectiveness of public services, to information retrieval systems that are able to support information requirements at lightning speed through various online media, to the state-of-the-art discoveries in fields such as nano technology and pervasive computing, which are expanding the horizons of what can be achieved with ICT.

The Ministry appreciates the efforts conducted by the organizing committee that has worked hard through this conference to achieve two important objectives towards the development of advanced computer science and information systems. Firstly, it is to disseminate the state of the art of research and development in ICT, cognizant of its significant value for Indonesia's future. Secondly, it is intended to provide a media for exchanging ideas and information concerning ICT. I am convinced that the scholars who have gathered here at this conference will bring valuable contributions to this discipline.

Finally, I want to convey my deep appreciation and gratitude to the Faculty of Computer Science, Universitas Indonesia, and all of our distinguished plenary and invited speakers. I hope this conference will be enlightening for all of us, and I hope also that we will be able to continuously collaborate to push the frontiers of science and solve the problems of our nation.

Sincerely,

**Professor Musliar Kasim**

**Vice Minister of Education**

**Ministry of Education and Culture of the Republic of Indonesia**

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## Program At Glance

<b>Saturday, December 17<sup>th</sup>, 2011 - CONFERENCE</b>				
<b>Time</b>	<b>Event</b>	<b>Event Details</b>		<b>Rooms</b>
07.30 – 08.30		Registration		Ballroom
08.30 – 09.05	Opening Ceremony	08.30–08.35	Preparation	
		08.35–08.45	Greeting from the Dean of Faculty of Computer Science Universitas Indonesia (Prof. T. Basaruddin, Ph.D.)	
		08.45–09.00	Keynote Speech and Official Opening by the Vice Minister of Education and Cultural Affairs (Prof. Musliar Kasim)	
		09.00-09.05	The souvenirs provision ceremony, from the Dean of Faculty of Computer Science, UI, Prof. T. Basaruddin, Ph.D. to the Vice Minister of Education and Cultural Affairs, Prof. Musliar Kasim	
09.05 - 09.45	Plenary Speech I	Prof. Boris Mirkin from National Research University Higher School of Economics, Moscow, Russian Federation Birkbeck University of London, UK.  Topic : Classical Statistics, Machine Learning, Data Mining and Data Analysis Perspectives: Similarities and Differences		
09.45 – 10.05		Coffee Break		
10.10 – 12.30	Parallel Session I: Four parallel sessions.	Included 40 minutes Invited Parallel Speech in Ballroom by Prof. Dr. Eng. Hajime Miyauchi from Kumamoto University, Japan.  Topic : Electric Power System Simulation  <b>See Technical Program(Parallel Session I Schedule)</b>		Ballroom, Room A, Room B, Room C.
12.30 – 13.30		Lunch		Ballroom

<b>Saturday, December 17<sup>th</sup>, 2011 - CONFERENCE</b>			
13.30 – 14.10	Plenary Speech II	Prof. Xue Li from School of Information Technology and Electrical Engineering, The University of Queensland  Topic : Recommendations based on Information Network Analysis	Ballroom
14.10– 14.50	Plenary Speech III	Ir. Zainal A. Hasibuan, MLS, Ph.D. from Faculty of Computer Science, Universitas Indonesia  Topic : Indonesian E-Cultural Heritage Framework : An Integrated Approach to Digital Preservation	Ballroom
14.50 – 15.20	Coffee Break		
15.20 – 16.20	Parallel Session II: Four parallel sessions.	Included 40 minutes Invited Parallel Speech in Ballroom by Bahtiar Alam, Ph.D, Director of Research and Community Services, Universitas Indonesia (DRPM UI)  Topic : Current Research Policy and Implementation at Universitas Indonesia  <b>See Technical Program (Parallel Session II Schedule)</b>	Ballroom, Room A, Room B, Room C.
16.20 – 18.40	Break		Ballroom
18.40 – 21.00	Gala Dinner	Dinner, accompanied by music performance and traditional dances	

<b>Sunday, December 18<sup>th</sup>, 2011 - CONFERENCE</b>			
<b>Time</b>	<b>Event</b>	<b>Event Details</b>	<b>Rooms</b>
07.30 – 08.00	Registration		Ballroom
08.00 – 08.40	Plenary Speech IV	Prof. Elena Gaura from Faculty of Engineering and Computing, Coventry University, UK.  Topic : Understanding the World Through Pervasive Sensing	Ballroom
08.40 - 09.00	Workshop registration		Ballroom
09.00 - 10.00	Workshop (hour 1)	<b>See Technical Program (Workshops Schedule)</b>	Ballroom, Room A, Room B, Room C.

<b>Sunday, December 18<sup>th</sup>, 2011 - CONFERENCE</b>				
<b>Time</b>	<b>Event</b>	<b>Event Details</b>		<b>Rooms</b>
10.00-10.30		Coffee Break		Ballroom
10.30 – 12.30	Workshop (hour 2 and 3)	<b>See Technical Program (Workshops Schedule)</b>		Ballroom, Room A, Room B, Room C.
12.30 – 13.30		Lunch		Ballroom
13.30 – 15.30	Parallel Session III: Four parallel sessions.	<p>Included 40 minutes Invited Parallel Speech in Ballroom by Prof.Dr.Ir. Bambang Riyanto Trilaksono, School of Electrical Engineering and Informatics, Bandung Institute of Technology</p> <p>Topic : Bio-inspired Computing for Modeling, Optimization and Control</p> <p><b>See Technical Program (Parallel Session III Schedule)</b></p>		Ballroom, Room A, Room B, Room C.
15.30 – 15.50		Coffee Break		Ballroom
15.50 – 16.30	Plenary Speech V	<p>Prof. Toshio Fukuda from Center for Micro-Nano Mechatronics Professor, Dept. of Micro-Nano Systems Engineering Nagoya University.</p> <p>Topic : Advanced service robotics for human assistance and support</p>		
16.30 – 17.00	Closing Ceremony (Award Announcement & Photo Session)	16.30-16.55	Closing ceremony and award announcement	
		16.55 - 17.00	Photo session	



## Table of Contents

Welcome Message from General Chairs	i
Welcome Message from Dean of Faculty of Computer Science University of Indonesia	iii
Welcome Message from Vice Minister of National Education and Culture	v
Committee	vii
Program At Glance	ix
Table of Content	xiii

### Plenary Lectures

Data Analysis, Mathematical Statistics, Machine Learning, Data Mining: Similarities and Differences	1
<i>Boris Mirkin</i>	
Recommendations based on Network Analysis	9
<i>Xue Li and Lin Cheng</i>	
Networked Body Sensing: Enabling real-time decisions in health and defence applications	17
<i>Ramona Rednic, John Kemp, Elena Gaura, and James Brusey</i>	
Advanced Service Robotics for Human Assistance and Support	25
<i>Toshio Fukuda, Pei Di, Fei Chen, Kousuke Sekiyama, Jian Huang</i>	
Indonesian E-Cultural Heritage Framework : An Integrated Approach to Digital Preservation	31
<i>Zainal A. Hasibuan</i>	

### Computer Networks, Architecture & High Performance Computing

Load Frequency Stabilization in two-area Interconnected System using CES and SSSC	37
<i>Saeid Jalilzadeh, Javad Gholinezhad, and Peyman Farhang</i>	

Optimization of Knowledge Sharing through Multi-Forum using Cloud Computing Architecture	43
<i>Sriram M.V. and Srivatsan Sankaran</i>	
Mobile Agent Implementation in Location-based Services	47
<i>Rendy Eka Saputra and Sri Wahjuni</i>	
Backscattering Control Logic Component Using FPGA Device	51
<i>Silmina Ulfah, Fiftatianti Hendajani, and Sunny Arief Sudiro</i>	
Optimal Quantization and Energy Allocation Schemes for Distributed Estimation in Wireless Sensor Networks	57
<i>Eni Dwi Wardihani, Wirawan, and Gamantyo Hendranto</i>	
An FPGA based Hardware Accelerator for Real Time Video Segmentation System	63
<i>Indra Yasri</i>	
A Distance Vector Algorithm for Wireless Sensor Networks by Combining Resource-Aware Framework	69
<i>Muhammad Ilyas Syarif, Jumadi M. Parenreng, Supeno Djanali, and Ary Masharuddin Shiddiqi</i>	
A Comparative Study on Operating System for Wireless Sensor Networks	73
<i>Thang Vu Chien, Hung Nguyen Chan, and Thanh Nguyen Huu</i>	
A Finite Volume Method for Shallow Water Flows on Triangular Computational Grids	79
<i>Sudi Mungkasi and Stephen Gwyn Roberts</i>	
Implementation of Parallel BACON-MVV Method based on Data Decomposition in Intrusion Detection System	85
<i>Lely Hiryanto, Andri Muliawan, and Dyah Erny Herwindiati</i>	
A Real Time Kernel for 16 bit PIC Microcontrollers	91
<i>Syed Kamal Mustafa</i>	
A Distributed Community Approach for Protecting Resources in Digital Ecosystem	95
<i>Ilung Pranata, Geoff Skinner, and Rukshan Athauda</i>	

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Effects of Impulsive Noise on Fourier Based OFDM and Wavelet Based OFDM	101
<i>Khaizuran Abdullah, Ahmad Fadzil Ismail, Md Rafiqul Islam, and Wahidah Hashim</i>	
Implementation Vehicle Classification On Distributed Traffic Light Control System Neural Network Based	107
<i>Big Zaman, Wisnu Jatmiko, Adi Wibowo, and Elly Matul</i>	
Telecommunication Networks Coverage Area Expansion in Disaster Area using Autonomous Mobile Robots : Hardware and Software Implementation	113
<i>E.Budianto, M.S, Alvissalim, A.Hafidh, A.Wibowo, W.Jatmiko, B.Hardian, P.Mursanto, and A.Muis</i>	
FNLVQ Design and Implementation in FPGA to Estimate Trichloroethylene in White Mouse Liver Images	119
<i>A. Febrian, M. Fajar, M.I. Tawakal, Elly Matul, W. Jatmiko, D.H. Ramdani, A. Bowolaksono, and P. Mursanto</i>	
<b>Digital Libraries and Distance Learning</b>	
Knowledge Engineering Approach for Constructing Ontology for e-Learning Services	125
<i>M.Farida Begam and Gopinath Ganapathy</i>	
Proposed Intelligent E-Learning System using Semantic Web	133
<i>Iman Paryudi and Sri Rezeki C.N.</i>	
<b>E-Government</b>	
Internet User Behavior Analysis in Online Shopping on Indonesia	137
<i>Nanang Husin</i>	
Design and Implementation of e-KTP (Indonesian Electronic Identity Card) Key Management System	143
<i>Aravada Kevindra Darwis and Charles Lim</i>	



A proposed methodology to develop an e-Government system based on Soft Systems Methodology (SSM) and Focus Group Discussion (FGD)	147
<i>Arief Ramadhan, Dana Indra Sensuse, and Aniati Murni Arymurthy</i>	
Semantic Web Based Distributed Government Data Center	153
<i>Imairi Eitiveni and Dana Indra Sensuse</i>	
 <b>Enterprise Computing</b>	
Modeling Serious Games based on Cognitive Skill Classification using Learning Vector Quantization with Petri Net	159
<i>Moh. Aries Syufagi , Mauridhi Hery P, and Mochamad Hariadi</i>	
Analytical Hierarchy Process and PROMETHEE Application in Measuring Object Oriented Software Quality	165
<i>Arwin Halim, Amin Sudrajat, Andry Sunandar, I Ketut Resika Arthana, Sunario Megawan, and Petrus Mursanto</i>	
Impact Analysis on Free Online Marketing Using Social Network Facebook: Case Study SMEs in Indonesia	171
<i>Putu Wuri Handayani and Wahyu Lisdianingrum</i>	
 <b>Formal Methods in Software Engineering</b>	
Multi Objectives Fuzzy Ant Colony Optimization of Palm Oil Based Bioenergy Supply Path Searching	177
<i>Ditdit N. Utama, TaufikDjatna, ErlizaHambali, Marimin, and Dadan Kusdiana</i>	
Computational Model of Social Interaction in Multi-agent Simulation based on Personality Traits	183
<i>Aswin Indraprastha</i>	
Model Simplification in Petri Net Models	189
<i>Reggie Davidrajuh</i>	

A Comparative Study of HNN and Hybrid HNN-PSO Techniques in the Optimization of Distributed Generation (DG) Power Systems	195
<i>Irraivan Elamvazuthi, T. Ganesan, and P. Vasant</i>	
A Short Overview on Modern Parallel SAT-Solvers	201
<i>Steffen Ho lldobler, Norbert Manthey, Van Hau Nguyen, Julian Stecklina, and Peter Steinke</i>	
Reverse Engineering Using Behavior Tree Approach	207
<i>Iis Solichah and Petrus Mursanto</i>	
Classification of Hospital Pharmaceutical Drugs Inventory Items by Combining ABC Analysis and Fuzzy Classification	215
<i>Mahendrawathi ER, Eliza Nurul Laili, and Renny P. Kusumawardani</i>	
<b>Information Retrieval</b>	
Model Selection For Time Series Forecasting Using Similarity Measure	221
<i>Agus Widodo and Indra Budi</i>	
Enriching Time Series Datasets using Nonparametric Kernel Regression to Improve Forecasting Accuracy	227
<i>Agus Widodo, Mohamad Ivan Fanani, and Indra Budi</i>	
Making Learning Ubiquitous With Mobile Translator Using Optical Character Recognition (OCR)	233
<i>Ariffin Abdul Muthalib, Anas Abdelsatar, Mohammad Salameh, and Juhriyansyah Dalle</i>	
Evaluation of Text-to-Speech Synthesizer for Indonesian Language Using Semantically Unpredictable Sentences Test: IndoTTS, eSpeak, and Google Translate TTS	237
<i>Nur Aziza Azis, Rose Maulidiyatul Hikmah, Teresa Vania Tjahja, and Anto Satriyo Nugroho</i>	
A Step Towards High Quality One-class Collaborative Filtering using Online Social Relationships	243
<i>Sirawit Sopchoke and Boonserm Kijirikul</i>	

Application of Document Spelling Checker for Bahasa Indonesia	249
<i>Aqsath Rasyid N., Mia Kamayani, Ridho Reinanda, Simon Simbolon, Moch Yusup Soleh, and Ayu Purwarianti</i>	
LinkedLab: A Linked Data Platform for Research Communities	253
<i>Fariz Darari and Ruli Manurung</i>	
Towards Data Warehouse Quality through Integrated Requirements Analysis	259
<i>Munawar, Naomie Salim, and Roliana Ibrahim</i>	
Developing Indonesian-English Hybrid Machine Translation System	265
<i>Evi Yulianti, Indra Budi, Achmad N. Hidayanto, Hisar M. Manurung, and Mirna Adriani</i>	
From XML view updates to ORSQL updates: Building updatable XML views over ORDBs	271
<i>Anuradha Karunasena and Prasanna S. Haddela</i>	
Wireless Sensor Networks Nodes Localization based on Inter-node RF Range Measurement using Vernier Effect	277
<i>Ali Husein Alasiry, Sang-Il Ko, Hong Phuoc Thanh, Jun-ya Takayama, and Shinji Ohyama</i>	
Expected Answer Type Construction using Analogical Reasoning in a Question Answering Task	283
<i>Hapnes Toba, Mirna Adriani, and Ruli Manurung</i>	
 <b>IT Governance</b>	
The Impact of Information Technology Governance Maturity Level on Corporate Productivity: a Case Study at an Information Technology Services Company	291
<i>Budi Yuwono and Annas Vijaya</i>	
Compliance Analysis of IT Investment Governance Practices to Val IT 2.0 Framework in Indonesian Commercial Bank: The XYZ Bank Case Study	297
<i>Larastrri Kumaralalita, Achmad Nizar Hidayanto, and Dina Chahyati</i>	

Factors Influencing Initial Trust Formation in Adopting Internet Banking in Indonesia 305

*Aries Susanto, Hwansoo Lee, and Hangjung Zo*

Designing a Tool for IT Governance Risk Compliance: A Case Study 311

*Dewi Puspasari, M. Kasfu Hammi, Muhammad Sattar, and Rein Nusa*

### **Pattern Recognition, Image Processing & Content-Based Image Retrieval System**

Application of a Hybrid Neural Network Model for Multispectral Remotely Sensed Image Classification in the Belopa Area South Sulawesi of Indonesia 317

*Muhamad Sadly and Yoke Faisal O.*

Real-Time Neural Network-Based Network Analyzer for Hotspot Area 323

*Rahmadya Trias Handayanto, Haryono, and Jarot Prianggono*

Haar Wavelet Decomposition Based Blockiness Detector and Picture Quality Assessment Method for JPEG Images 331

*Irwan Prasetya Gunawan and Antony Halim*

Recursive Text Segmentation for Color Images for Indonesian Automated Document Reader 337

*Teresa Vania Tjahja, Anto Satriyo Nugroho, Nur Aziza Azis,*

*Rose Maulidiyatul Hikmah, and James Purnama*

Enhancement of Trabecular Bone on Dental Panoramic Radiographs Using Multiscale Line Operator 343

*Agus Zainal Arifin, Dwi Izzatul Millah, Imam Cholissodin, and Indra Lukmana*

Automated Status Identification of Microscopic Images Obtained from Malaria Thin Blood Smears using Bayes Decision: A study case in Plasmodium Falciparum 347

*Dian Anggraini, Anto Satriyo Nugroho, Christian Pratama,*

*Ismail Ekoprayitno Rozi, Vitria Pragesjvara, and Made Gunawan*

Evaluation of Fingerprint Orientation Field Correction Methods 353

*Andree A. K. Surya, Anto S. Nugroho, and Charles Lim*

A Normalization Method of Converting Online Handwritten Chinese Character to Stroke- Segment-Mesh Glyph	359
<i>Hanquan Huang</i>	
Optimal Selection of Wavelet Thresholding Algorithm for ECG Signal Denoising	365
<i>Sani M. Isa, Ary Noviyanto, and Aniat Murni Arymurthy</i>	
Vision-Based Navigation Using Top-view Transform and Beam-ray Model	371
<i>Qing Lin, Youngjoon Han, and Hernsoo Hahn</i>	
Non-Invasive Intracranial Pressure Classification Using Strong Jumping Emerging Patterns	377
<i>Putu Wira Angriyasa, Zuherman Rustam, and Wismaji Sadewo</i>	
Monitoring of Molten Pool Image during Pipe Welding in Gas Metal Arc Welding (GMAW) Using Machine Vision	381
<i>Ario Sunar Baskoro, Erwanto, and Winarto</i>	
Arrhythmia Classification using Fuzzy-Neuro Generalized Learning Vector Quantization	385
<i>I Made Agus Setiawan, Elly M. Imah, and Wisnu Jatmiko</i>	
Detection of Visual Bearing Defect Using Integrated Artificial Neural Network	391
<i>Agustian K. Herdianta and Aulia M.T. Nasution</i>	
Web-Based Decision Support System Using C4.5 Decision Tree Algorithm	395
<i>Rajesri Govindaraju and Dipta Mahardhika</i>	

### **Poster Session**

On Performance of Kernel Based and Embedded Real-Time Operating System: Benchmarking and Analysis	401
<i>Mastura D. Marieska, Paul G. Hariyanto, M. Firda Fauzan, Achmad Imam Kistijantoro, and Afwarman Manaf</i>	

Skin Color Segmentation Using Adaptive PCA and Modified Elliptic Boundary Model 403

*Noha A.Hikal and Roumen Kountchev*

The Effect of Syllable and Word Stress on the Quality of Indonesian HMM-based  
Speech Synthesis System 413

*Clara Vania and Mirna Adriani*



# A Finite Volume Method for Shallow Water Flows on Triangular Computational Grids

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**Abstract**—This paper presents a finite volume method used to solve the two-dimensional shallow water (wave) equations and how the finite volume method is implemented in ANUGA software. This finite volume method is the numerical method underlying the software. ANUGA is open source software developed by Australian National University (ANU) and Geoscience Australia (GA). This software uses the finite volume method with triangular domain discretisation for the computation. Three test cases are considered in order to evaluate the performance of the software. Overall, ANUGA is a robust software to simulate two-dimensional shallow water flows.

## I. INTRODUCTION

THE shallow water (wave) equations have emerged as important mathematical models to describe water flows. Some of its developments and applications are given in [1], [2], [3], [4].

One old work with a big impact is the analytical dam break modelling done by Ritter [5]. The dam break problem is now becoming a standard benchmark to test the performance of numerical methods. Even though this problem is originally modelled for one-dimensional shallow water equations, it can also be treated as a two-dimensional problem, which we present in this paper as a planar dam break problem. In addition, it can also be extended to a circular two-dimensional problem.

Another interesting benchmark problem is the oscillation of water on a paraboloid canal (channel) developed by Thacker [6]. This problem involves a wetting and drying process, a process that is well-known to be very difficult to resolve [7], [8], [9], [10], [11]. We note that Yoon and Cho [12] used this type of problem to test their numerical method.

One open-source software used to simulate two-dimensional shallow water flows is ANUGA, named after Australian National University (ANU) and Geoscience Australia (GA). This software uses a finite volume method as the underlying mathematical background. We will present this finite volume method and test the performance of ANUGA using the planar dam break problem, circular dam break problem, and oscillation on a paraboloid channel. ANUGA uses triangular domain discretisation for the computation.

The remainder of this paper is organised as follows. In Section II, we present the shallow water equations governing water flows. Section III is devoted to the finite volume method. Section IV briefly describes the ANUGA software. Section V contains three numerical simulations. Finally, Section VI concludes the paper with some remarks.

## II. SHALLOW WATER EQUATIONS

The two-dimensional shallow water (wave) equations are [13], [14], [15], [16], [17], [18]

$$\mathbf{q}_t + \mathbf{f}(\mathbf{q})_x + \mathbf{g}(\mathbf{q})_y = \mathbf{s}, \quad (1)$$

where  $\mathbf{q} = [h \ uh \ vh]^T$  is the vector of conserved quantities consisting of water depth  $h$ ,  $x$ -momentum  $uh$ , and  $y$ -momentum  $vh$ . Here,  $u$  and  $v$  are velocities in the  $x$ - and  $y$ -direction;  $\mathbf{f}(\mathbf{q})$  and  $\mathbf{g}(\mathbf{q})$  are flux functions in the  $x$ - and  $y$ -direction given by

$$\mathbf{f}(\mathbf{q}) = \begin{bmatrix} uh \\ u^2h + \frac{1}{2}gh^2 \\ uvh \end{bmatrix} \quad (2)$$

and

$$\mathbf{g}(\mathbf{q}) = \begin{bmatrix} vh \\ vuh \\ v^2h + \frac{1}{2}gh^2 \end{bmatrix}; \quad (3)$$

the source term including gravity and friction is

$$\mathbf{s} = \begin{bmatrix} 0 \\ -gh(z_x + S_{fx}) \\ -gh(z_y + S_{fy}) \end{bmatrix} \quad (4)$$

where  $z(x, y)$  is the bed topography, and  $S_f = \sqrt{S_{fx}^2 + S_{fy}^2}$  is the bed friction modelled using Manning's resistance law

$$S_{fx} = \frac{u\eta^2\sqrt{u^2 + v^2}}{h^{4/3}} \quad (5)$$

and

$$S_{fy} = \frac{v\eta^2\sqrt{u^2 + v^2}}{h^{4/3}} \quad (6)$$

in which  $\eta$  is the Manning resistance coefficient. It should be noted that the stage (absolute water level)  $w$  is given by  $w := z + h$ .



Integrating (1) over an arbitrary closed and connected spatial domain  $\Omega$  having boundary  $\Gamma$  and applying the Gauss divergence theorem to the flux terms, we get the integral form

$$\frac{\partial}{\partial t} \int_{\Omega} \mathbf{q} d\Omega + \oint_{\Gamma} \mathbf{F} \cdot \mathbf{n} d\Gamma = \int_{\Omega} \mathbf{s} d\Omega \quad (7)$$

where  $\mathbf{F} = [\mathbf{f}(\mathbf{q}) \ \mathbf{g}(\mathbf{q})]^T$  is the flux function,  $\mathbf{n} = [\cos(\theta) \ \sin(\theta)]^T$  is the outward normal vector of the boundary, and  $\theta$  is the angle between  $\mathbf{n}$  and the  $x$ -direction. Equation (7) is called the integral form of the two-dimensional shallow water wave equations.

The rotational invariance property of the shallow water wave equations implies that

$$\mathbf{F} \cdot \mathbf{n} = \mathbf{T}^{-1} \mathbf{f}(\mathbf{T}\mathbf{q}) \quad (8)$$

where  $\mathbf{T}$  is the transformation matrix

$$\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & \sin(\theta) \\ 0 & -\sin(\theta) & \cos(\theta) \end{bmatrix}. \quad (9)$$

Therefore, (7) can be rewritten as

$$\frac{\partial}{\partial t} \int_{\Omega} \mathbf{q} d\Omega + \oint_{\Gamma} \mathbf{T}^{-1} \mathbf{f}(\mathbf{T}\mathbf{q}) d\Gamma = \int_{\Omega} \mathbf{s} d\Omega. \quad (10)$$

### III. FINITE VOLUME METHOD

After the spatial domain is discretized, we have the equation constituting the finite volume method over each triangular cell of the grids [14]

$$\frac{d\mathbf{q}_i}{dt} + \frac{1}{A_i} \sum_{j \in \mathcal{N}(i)} \mathbf{H}_{ij} l_{ij} = \mathbf{s}_i \quad (11)$$

where  $\mathbf{q}_i$  is the vector of conserved quantities averaged over the  $i$ th cell,  $\mathbf{s}_i$  is the source term associated with the  $i$ th cell,  $\mathbf{H}_{ij}$  is the outward normal flux of material across the  $ij$ th edge, and  $l_{ij}$  is the length of the  $ij$ th edge. Here, the  $ij$ th edge is the interface between the  $i$ th and  $j$ th cells. The flux  $\mathbf{H}_{ij}$  is evaluated using a numerical flux function  $\mathbf{H}(\cdot, \cdot; \cdot)$  such that for all conservation vectors  $\mathbf{q}$  and normal vectors  $\mathbf{n}$

$$\mathbf{H}(\mathbf{q}, \mathbf{q}; \mathbf{n}) = \mathbf{F} \cdot \mathbf{n}. \quad (12)$$

Furthermore,

$$\mathbf{H}_{ij} = \mathbf{H}(\mathbf{q}_i(m_{ij}), \mathbf{q}_j(m_{ij}); \mathbf{n}_{ij}) \quad (13)$$

where  $m_{ij}$  is the midpoint of the  $ij$ th edge and  $\mathbf{n}_{ij}$  is the outward normal vector, with respect to the  $i$ th cell, on the  $ij$ th edge. The function  $\mathbf{q}_i$  is obtained from the averaged values of quantities in the  $i$ th and neighbouring cells.

Now let  $\mathbf{n}_{ij} = [n_{ij}^{(x)} \ n_{ij}^{(y)}]^T$ . From (12) and (13), we have

$$\mathbf{H}_{ij} = \mathbf{f}[\mathbf{q}_i(m_{ij})]n_1 + \mathbf{g}[\mathbf{q}_j(m_{ij})]n_2 \quad (14)$$

Here, we recall the algorithm to solve the two-dimensional shallow water equations given by Guinot [13]. In the semi-discrete framework, four steps are considered as follows:

- 1) For each interface  $(i, j)$ , transform the quantity  $\mathbf{q}_i$  and  $\mathbf{q}_j$  in the global coordinate system  $(x, y)$  into the quantity  $\hat{\mathbf{q}}_i$  and  $\hat{\mathbf{q}}_j$  in the local coordinate system  $(\hat{x}, \hat{y})$ . The water depth  $h$  is unchanged as it is a scalar variable, while the velocities  $u$  and  $v$  are transformed into  $\hat{u}$  and  $\hat{v}$ . Therefore, the new quantities in the local coordinate system are

$$\hat{\mathbf{q}}_i = \mathbf{T}\mathbf{q}_i \quad \text{and} \quad \hat{\mathbf{q}}_j = \mathbf{T}\mathbf{q}_j, \quad (15)$$

where  $\mathbf{q}_i = [h_i \ (hu)_i \ (hv)_i]$  and  $\mathbf{q}_j = [h_j \ (hu)_j \ (hv)_j]$  are, respectively, the quantities in the global coordinate system. The matrices  $\mathbf{T}$  and  $\mathbf{T}^{-1}$  are

$$\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & n_{ij}^{(x)} & n_{ij}^{(y)} \\ 0 & -n_{ij}^{(y)} & n_{ij}^{(x)} \end{bmatrix} \quad (16)$$

and

$$\mathbf{T}^{-1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & n_{ij}^{(x)} & -n_{ij}^{(y)} \\ 0 & n_{ij}^{(y)} & n_{ij}^{(x)} \end{bmatrix}. \quad (17)$$

- 2) Compute the flux  $\hat{f}$  at the interface  $(i, j)$ . In the local coordinate system, the problem is merely a one-dimensional Riemann problem, as the flux vector is parallel with the normal vector of the interface. Therefore, the equations to be solved are

$$\hat{\mathbf{q}}_t + \hat{\mathbf{f}}(\hat{\mathbf{q}})_{\hat{x}} = \mathbf{s} \quad (18)$$

with initial condition given by  $\hat{\mathbf{q}}_i$  on one side of the interface  $(i, j)$  and  $\hat{\mathbf{q}}_j$  on the other side of the interface  $(i, j)$ . It should be stressed that at this step, we do not need to integrate (18) for the quantity  $\hat{\mathbf{q}}$ , but all we need is the value of the flux  $\hat{f}$ . Hence, applying either the exact or approximate Riemann solvers to compute the flux  $\hat{f}$  at the interface  $(i, j)$  is enough. Note that here the source term does not need to be transformed in the local coordinate system, since it involves scalar variables only.

- 3) Transform the flux  $\hat{\mathbf{f}}$  back to the global coordinate system  $(x, y)$ , so the flux at the midpoint of the interface  $(i, j)$  in the global coordinate system is

$$\begin{aligned} \mathbf{H}_{ij} &= \mathbf{T}_{ij}^{-1} \hat{\mathbf{f}} \\ &= \mathbf{T}_{ij}^{-1} \tilde{\mathbf{f}}(\hat{\mathbf{q}}_i; \hat{\mathbf{q}}_j; \mathbf{s}_i; \mathbf{s}_j) \\ &= \mathbf{T}_{ij}^{-1} \tilde{\mathbf{f}}(\mathbf{T}_{ij}\mathbf{q}_i; \mathbf{T}_{ij}\mathbf{q}_j; \mathbf{s}_i; \mathbf{s}_j). \end{aligned} \quad (19)$$

Here,  $\tilde{\mathbf{f}}$  is the flux computed with a Riemann solver for the one-dimensional problem stated in step [ii].

- 4) Finally, solve (11) where  $\mathcal{N}(i) = \{0, 1, 2\}$ , as triangular grids are considered, for  $\mathbf{q}_i$ . We multiply  $\mathbf{H}_{ij}$  with  $l_{ij}$  in order to get the flux over the interface  $(i, j)$ . This is because the flux

at the midpoint of the interface  $(i, j)$  is  $\mathbf{H}_{ij}$ , and the length of the interface  $(i, j)$  is  $l_{ij}$ .

#### IV. ANUGA SOFTWARE

ANUGA is an open source (free software) developed by Australian National University (ANU) and Geoscience Australia (GA) to be used for simulating shallow water flows, such as floods and tsunamis. The mathematical background underlying the software is the finite volume method presented in the previous section. The interface of this software is in Python language, but the mostly expensive computation parts, such as flux computation, are written in C language. A combination of these two languages provides two different advantages: Python has the flexibility in terms of software engineering, while C gives a very fast computation.

A simple simulation using ANUGA generally has five steps in the interface code. These five steps are importing necessary modules, setting-up the computational domain, setting-up initial conditions, setting-up boundary conditions, and evolving the system through time [14]. The necessary modules to be imported are `anuga`<sup>1</sup> and some standard libraries such as `numpy`, `scipy`, `pylab`, and `time`. The simplest creation of the triangular computational domain is in the rectangular-cross framework, which returns points, vertices, and boundary for the computation. The initial condition includes the definition of the topography, friction, and stage. The boundary conditions can be chosen in several ways depending on the needs: reflective boundary is for solid reflective wall; transmissive boundary is for continuing all values on the boundary; Dirichlet boundary is for constant boundary values; and time boundary is for time dependent boundary.

A thorough description of this software is available at <http://datamining.anu.edu.au/anuga>.

#### V. COMPUTATIONAL EXPERIMENTS

This section presents some computational experiments using the finite volume method with ANUGA as the software used to perform the simulation. For simplicity of the experiments, frictionless topography is assumed. Three different test cases are considered: a planar dam break problem, circular dam break problem, and water oscillation on a paraboloid channel.

The numerical settings are as follows. Even though ANUGA is capable to do the computations with unstructured triangular grids, we limit our presentation only to the structured triangular grids for brevity with rectangular-cross as the basis. The spatial reconstruction and temporal discretisation are both second order with edge limiter. A reflective boundary is imposed. The numerical flux is due to Kurganov et al.[19]. SI units are used in the measurements of the quantities.

<sup>1</sup>Uppercased word 'ANUGA' refers to the name of the software, whereas lowercased word 'anuga' refers to the name of ANUGA module in programming. See ANUGA User Manual [14] for the details of anuga.



Fig. 1. Initial condition for the planar dam break problem.

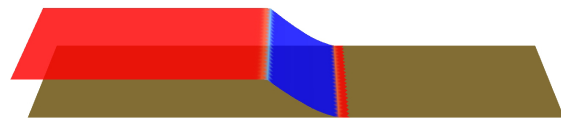


Fig. 2. Water flows 0.5 second after the planar dam is broken.

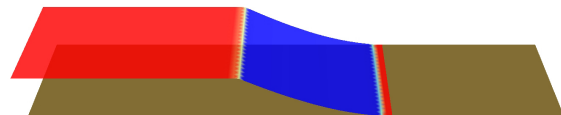


Fig. 3. Water flows 1.0 second after the planar dam is broken.

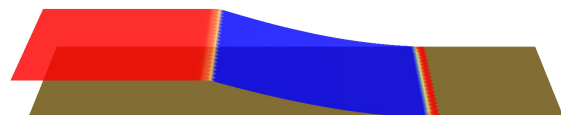


Fig. 4. Water flows 1.5 seconds after the planar dam is broken.

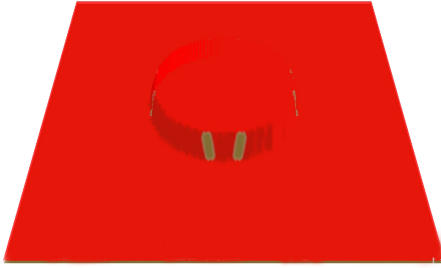


Fig. 5. Initial condition for the circular dam break problem.

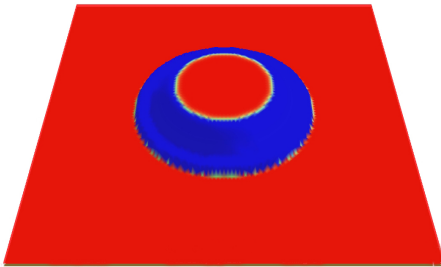


Fig. 6. Water flows 0.5 second after the circular dam is broken.

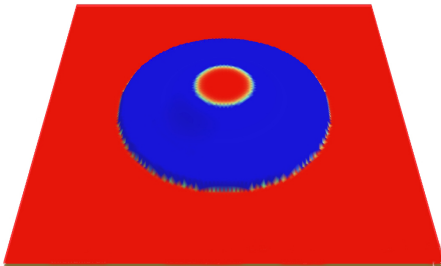


Fig. 7. Water flows 1.0 second after the circular dam is broken.

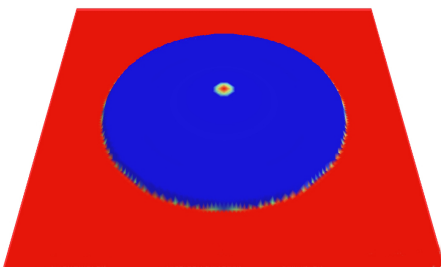


Fig. 8. Water flows 1.5 seconds after the circular dam is broken.

#### A. Planar dam break problem

Consider a flat topography without friction on a spatial domain  $\{(x, y) | (x, y) \in [-50, 50] \times [-10, 10]\}$ . Suppose that we are given a planar dam break problem with wet/dry interface between the dam, where we have 10 meters water depth on the left of the dam, but dry area on the right. The dam is at  $\{(0, y) | y \in [-10, 10]\}$ . The simulation is then done to predict the flow of water after the dam is removed. Note that this dam break problem is actually a one-dimensional dam-break problem, but here we treat this as a two-dimensional problem.

The domain setting is as follows. The spatial domain is discretised into 100 by 20 rectangular-crosses, where each rectangular cross has 4 uniform triangles. This means that we have  $8 \cdot 10^3$  structured triangles as the discretisation of the spatial domain.

The water surface and topography are shown in Figures 1 to 4. In particular, Figure 1 shows the initial condition, that is, the water profile at time  $t = 0.0$  s. After the dam is broken, the profiles at time  $t = 0.5, 1.0, 1.5$  s are illustrated in Figure 2, Figure 3, and Figure 4 respectively. At 1.5 seconds after dam break, the water flows to the right for a distance almost 30 m. This agrees with the analytical solution (30 m) for the one-dimensional dam break problem.

#### B. Circular dam break problem

Now suppose that we have a circular dam break problem with wet/wet interface between the dam. Consider a circular dam, where the point of origin is the centre, having 20 m as its radius. The water depth inside the circular dam is 10 m, while outside is 1 m. The spatial domain of interest is  $\{(x, y) | (x, y) \in [-50, 50] \times [-50, 50]\}$ . Similar to the planar dam break problem, the simulation of this test case is then done to predict the flow of water, after the dam is removed.

The domain setting is as follows. The spatial domain is discretised into 100 by 100 rectangular-crosses, where each rectangular cross has 4 uniform triangles. This means that we have  $4 \cdot 10^4$  structured triangles as the discretisation of the spatial domain.

The water surface and topography are shown in Figures 5 to 8. In particular, Figure 5 shows the initial condition, that is, the water profile at time  $t = 0.0$  s. After the dam is broken, the profiles at time  $t = 0.5, 1.0, 1.5$  s are illustrated in Figure 6, Figure 7, and Figure 8 respectively. At 1.5 seconds after dam break, the water floods to the surrounding area approximately 25 m outwards.

#### C. Oscillation on a paraboloid channel

This test case is adapted from the work of Thacker [6] and Yoon and Chou [12]. Suppose that we have a spatial domain  $\{(x, y) | (x, y) \in [-4000, 4000] \times [-4000, 4000]\}$ . We define some parameters  $D_0 =$

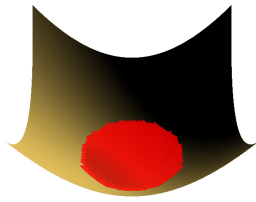


Fig. 9. Initial condition for the oscillation problem.

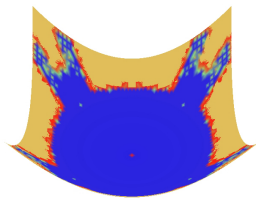


Fig. 10. Water flows at time  $t = 0.5T$  for the oscillation problem.

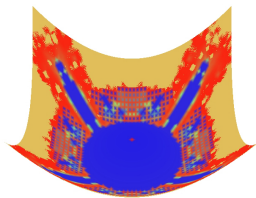


Fig. 11. Water flows at time  $t = T$  for the oscillation problem.

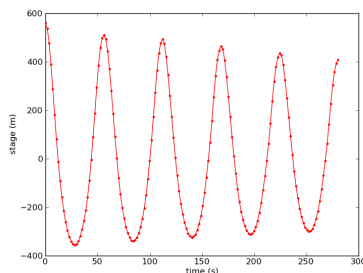


Fig. 12. The water surface corresponding to the origin until  $t = 5T$  for the oscillation problem.

1000,  $L = 2500$ ,  $R_0 = 2000$  such that

$$A = \frac{L^4 - R_0^4}{L^4 + R_0^4}, \quad (20)$$

$$\omega = \frac{2}{L\sqrt{2gD_0}}, \quad (21)$$

$$T = \frac{2\pi}{\omega} \quad (22)$$

are the amplitude of oscillation at the origin, the angular frequency, and the period of oscillation. Furthermore, the topography is given by

$$z(x, y) = -D_0 \left( 1 - \frac{r^2}{L^2} \right) \quad (23)$$

and the initial water level (the initial wet region) is

$$h(x, y) = D_0 \left[ \frac{\sqrt{1 - A^2}}{1 - A \cos(\omega t)} - 1 - \frac{r^2}{L^2} \left( \frac{1 - A^2}{(1 - A \cos(\omega t))^2} - 1 \right) \right] \quad (24)$$

where

$$r = \sqrt{x^2 + y^2}. \quad (25)$$

The domain setting is as follows. The spatial domain is discretised into 50 by 50 rectangular-crosses, where each rectangular cross has 4 uniform triangles. This means that we have  $10^4$  structured triangles as the discretisation of the spatial domain.

The simulation is then done to predict the flow of the water. According to Thacker [6], the flow will be a periodic oscillation. The simulation, using the numerical method and software discussed in this paper, indeed shows this periodic motion. The water profiles at time  $t = 0, T/2, T$  are shown in Figure 9, Figure 10, and Figure 11 respectively. In addition, the periodic motion of the water surface corresponding to the origin is depicted in Figure 12. From the numerical results, we see a minor damping of the oscillation. However, a perfect method or software should not produce this damping. Although it may be impossible to have a perfect method, we take this for future research for the ANUGA software to minimise or eliminate this kind of damping. We also see from the numerical results that a negligible amount of water is left over in the supposed-dry area.

## VI. CONCLUSIONS

This paper has presented a finite volume method used to solve the shallow water equations. The method underlies ANUGA software. ANUGA was tested using three numerical simulations. We infer from the simulation results that ANUGA can solve nicely the wetting problem. For the drying problem, some very small amount of water, which is negligible, may be left over on the supposed-dry area. Regardless of what we have investigated, we need to note that different parameters or numerical settings generally lead to different results.

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