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Prof. Radu Popescu-Zeletin
Fraunhofer Institute for Open Communication Systems
Technical University Berlin
Germany
rpz@cs.tu-berlin.de
Prof. Athanasios D. Styliadis
Alexander Institute of Technology
Thessaloniki
Agiou Panteleimona 24, 551 33, Thessaloniki, Greece
styl@it.teithe.gr
Prof. Horia-Nicolai Teodorescu
Faculty of Electronics and Telecommunications
Technical University "Gh. Asachi" Iasi
Iasi, Bd. Carol I 11, 700506, Romania
hteodor@etc.tuiasi.ro
Prof. Imre J. Rudas
Institute of Intelligent Engineering Systems
Budapest Tech
Budapest, Bécsi út 96/B, H-1034, Hungary
rudas@bmf.hu
Dr. Gheorghe Tecuci
Center for Artificial Intelligence
George Mason University
University Drive 4440, VA 22030-4444, U.S.A.
tecuci@gmu.edu
Dr. Dan Tufiş
Research Institute for Artificial Intelligence
of the Romanian Academy
Bucharest, "13 Septembrie" 13, 050711, Romania
tufis@racai.ro

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From Algorithms to (Sub-)Symbolic Inferences in Multi-Agent Systems

Boldur E. Bărbat, Sorin C. Negulescu

Abstract: Extending metaphorically the Moisilean idea of "nuanced-reasoning logic" and adapting it to the e-world age of Information Technology (IT), the paper aims at showing that new logics, already useful in modern software engineering, become necessary mainly for Multi-Agent Systems (MAS), despite obvious adversities. The first sections are typical for a position paper, defending such logics from an *anthropocentric perspective*. Through this sieve, Section 4 outlines the features asked for by the paradigm of *computing as intelligent interaction*, based on *"nuances of nuanced-reasoning"*, that should be reflected by agent logics. To keep the approach credible, Section 5 illustrates how *quantifiable synergy* can be reached - even in advanced challenging domains, such as *stigmergic coordination* - by injecting symbolic reasoning in systems based on sub-symbolic "emergent synthesis". Since for *future work* too the preferred logics are doxastic, the *conclusions* could be structured in line with the well-known agent architecture: Beliefs, Desires, Intentions.
Keywords: Nuanced-reasoning logic, Multi-Agent Systems, Sub-symbolic inferences, Stigmergic coordination, Synergy

1 Introduction. From Chrysippus, via Moisil, to Agent Logics

For over 40 years, *determinism and bivalence* of Chrysippean logic were the pillars of Computer Science; likewise, algorithms were the backbone of computer programs, complying with their etymon: *pro-gramma = what is written in advance*. They sufficed for both FORTRAN-like number crunching and COBOL-like business data processing. When early real-time applications (firstly, operating systems) required less autistic programs, algorithms tried to adapt and bizarre terms, such as "unsolicited input", were coined to fit the incipient non-determinism due to user free will. Bivalence not only survived, but also grew in importance strongly backed by hardware. Indeed, in the early 70's, the role of bivalent logic transcended the borders of narrow data processing, penetrating "Computer-Aided x", where x stays for almost any intellectual activity. Thus, "algorithmic reasoning", instead of being perceived as a side effect of "analogue humans loosing the battle with digital computers", became a paradigm in the very sense of Kuhn.

Emerging within this "digital Zeitgeist", nuanced-reasoning [12] was too anti-paradigmatic to redress the balance - at least in IT (besides, it was technologically useless, as most fascinating heresies). Only after the "PC-Windows-WWW" revolution was this "nuanced" kind of fuzzy logic - developed by Zadeh as "computing with words" - acknowledged as an alternative approach to software development (albeit seldom necessary).

On the other hand, after a decade of success stories, within artificial intelligence (AI) - the perpetual stronghold of applied logics and symbolic processing -, expert systems (based on the Newell-Simon hypothesis) began to disappoint, because of their brittleness (in all nuances of the word), showing the actual limits of the symbolic paradigm. The reaction was prompt, overwhelming, and exaggerated: "GOFAI" (*G*ood *O*ld-*F*ashioned *AI*) has to be replaced by "BIC" (*B*iologically *I*nspired *C*omputing), based on sub-symbolic paradigms. The most nihilist and powerful one, i.e. the ethological paradigm (based on the physical-grounding hypothesis), is, for good reasons, still in vogue. However, paradoxically, new, "much nuanced" logics are already used in modern software engineering, tending to become necessary mainly for non-trivial MAS, despite many, major, and obvious adversities.

The paper aims to: a) defend not just those logics but also the inexorable need of symbolic processing,

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even in systems where intelligent behaviour emerges sub-symbolically (because of its synergistic potential); b) after explaining *why* synergy, show *how* it can be reached. (That is why the title contains the unusual term "(Sub-)Symbolic".) Thus, after a short *history* (Section 2), the *approach* is rendered from an anthropocentric perspective: the agent shall behave naturally (i.e., closer to human behaviour), not the opposite (Section 3). Through this sieve, Section 4 outlines the features and symbolic mechanisms asked for by the paradigm of "computing as intelligent interaction", based on "*nuances of nuanced-reasoning"*. To keep the approach credible, Section 5 sums up recent research showing how *quantifiable interparadigmatic synergy* can be reached - even in advanced challenging domains, such as *stigmergic coordination* - by injecting symbolic reasoning in systems based on sub-symbolic "emergent synthesis". Since for future work the preferred logics are doxastic, the *conclusions* (Section 6) - far from being apodictic - can be structured in line with the well-known agent architecture: Beliefs, Desires, Intentions.

2 History. In Search of Synergy

The research roots are in over 20 papers/articles published in 1997-2002 and synthesised in [3]. After 2002 there are two history strands having the common denominator "looking for synergy in the world of humans and agents":

- *Stigmergic Coordination*. After minor improvements in 2003, in [13] some (less quantifiable) synergy was achieved deviating from the biological model applied in the Elitist Ant Systems by adding symbolic processing components (firstly adapting the environment and secondly instituting limited central coordination). In [7] a refined experimental model attested that in operational research, through "stigsynergy" the same solution quality could be reached with fewer ants than used in common benchmarks, saving thus at least one order of magnitude of processing time.

- *Human-Agent Communication*. User-avatar interaction was illustrated in medical captology, employing pathematic agents as virtual therapists [4]. The framework was widened (in the context of broadband communication) to any anthropocentric interface in [5], focusing on the languages enabled by modern multimodal interfaces. On a more abstract level, [6] showed how trans-disciplinary metaphors, applied in communication procedures, can help humanists and technologists get close.

3 Approach. Towards Natural Behaviour of Artificial Entities

Two perspectives guide the approach: anthropocentric systems, as non-negotiable goal, and agent-oriented software engineering (AOSE), as amendable means - depending on long-range effectiveness. (*Anthropocentrism* means focusing on the human being as user, beneficiary, and, ultimately, *raison d'être* of any application or, more general, technology [5]. Here, *"anthropocentric"* is synonymous to *"human-centred"*). The *premises* are:

1. *Regarding the goal:*

   - Despite their fast rising technological level, most IT applications involving intense human-computer interaction (HCI) have low degree of user acceptance, ignoring the very slogan: "computing as interaction" [1].
   - That drawback holds mainly for AI systems, widening the gap between humanists and technologists.
   - The main cause: system development is rather *techno*centric than *anthropo*centric.

- The main neglected human features are: $1^{\star}$) Invariants: humans are intrinsically analogue in information processing and multimodal in perception. $2^{\star}$) Prevalent in HCI: humans prefer symbolic communication but sub-symbolic response.

2. *Regarding the means:*

   - The IT infrastructure is sufficiently advanced (in both facts and trends: nanoelectronics, broadband communication, semantic web, multimodal interfaces, etc.) to allow anthropocentrism for most IT applications.
   - Intelligent system behaviour - whatever that could mean - becomes a crucial user expectation. Regrettably, in AI neither technology, nor design philosophy were yet able to offer it in a user-relevant manner.
   - Nevertheless, agent technology, as AI flagship, proved to be a significant step towards user acceptance.
   - AOSE is not bounded to AI, but tends to become the dominant IT development paradigm [11], [15].

While the first premises in each category are generally accepted, the last ones are debatable (e.g., A4b is rather an "author thesis" and B4 is strongly contested by object-oriented designers). The *corollaries* relevant for the paper are:

- C1. The geometrically increasing computing power (due to Moore's law) promotes at least five factors tending to reduce radically the role of any species of logic in IT - at least for applications affordable on usual configurations:

  1. Since deterministic applications are vanishing, the conventional algorithm is not anymore *program backbone*.
  2. Even when still useful, the conventional algorithm is not anymore the main *programming instrument* (being hidden in procedures easily reached in a host of libraries or being generated by 4GL).
  3. In AI the *symbolic* paradigm is steadily replaced by several *sub-symbolic* ones, based on fine-grain parallelism.
  4. Even when symbols are used, they are *stored* in and *retrieved* from huge and cheap memory, rather than *processed* through sophisticated reasoning schemes (case-based reasoning is just a blatant example).
  5. Cognitive *complexity* of new, sophisticated logics is too high for a designer, when "cut and try" is affordable.

- C2. The rules for human-agent interaction can and should be set by users (at least while we have the Demiurgic privilege of shaping agents as we like it!):

  1. Since *interaction* is carried out through the *interface*, anything behind it is user-irrelevant.
  2. Since *natural* and artificial *intelligence* encounter at interface level, they shall *join*, not *collide*.
  3. To join closer to human demeanour, users should engage interface agents as *naturally* as possible.
  4. Hence, let agents *behave* more and more *naturally* (e.g., it is not difficult to go beyond gestures to show emotivity, since not *emotion* has to be replicated, but its *appearance* - firstly forged, later more genuine [5]).

5. Since *interaction* involves *communication*, the *communication procedures* (the term "procedures" is here a prudent, albeit partial, place holder for "language" or, even, "empathy") must be those humans are familiar with (e.g., body language can and shall be added to verbal messages).
6. Since beside *how* to communicate (the vehicle), it is vital *what* (the message), beyond the *procedures*, there must be a *representational compatibility* between humans and agents (expressed through common ontologies, primitive surrogate of a yet impossible common "Weltanschauung").

If regarding C2.1-C2.4, the blend "symbolic/sub-symbolic" is unclear, C2.5 implies symbols, whereas C2.6 is stronger, implying symbolic inferences. At least some of them shall be based on logic(s).
For short, acknowledging the decline of logic (because of C1), its necessity is asserted (in line with C2). Anyway, the role of desirable features of new logics could be credibly defended - outside large-scale systems, were the proof is futile - only comparing diverse implemented MAS designed with or without employing such logics. Because of C1.5, this is impractical. To weaken this main approach drawback, the argument is split to render two complementary paths, both based on the idea that the blend "symbolic/sub-symbolic" yields synergy: a) axiological perspective: why and what symbolic processing (Section 4, closer to a position paper); b) praxiological perspective: how can symbolic processing be added in experimental sub-symbolic models (Section 5, closer to a technical report).

4 Nuances of Nuanced-Reasoning in Human-Agent Dialogue

It would be both arrogant and absurd if authors lacking educational background in both mathematics and logic would utter value judgments in these fields. Hence:

- Without claiming that Moisil actually attached to *"nuanced"* other connotation than *"fuzzy"*, bearing in mind his gifted baroque way of catalysing brainstorming, it is legitimate to use undertones of three (partial) synonyms - *"degree"*, *"gradation (sequence, development)"*, *"fine distinction"* - as metaphor sources.
- All assertions about existing or desirable logics mirror the angle of potential users of such logics, mainly in interface agents and MAS based on stigmergy. They convey "calls for help", not requests, and are uttered as desires.
- Since, as regards logics dealing with agent-related aspects, for many basic AOSE requests, Fisher's logic [9] seems for a non-specialist by far to be the most responsive and appropriate, all desiderata below refer to it.

■ **Diversified inferences.** Smith's propositional-representation theory should be: a) revisited and thoroughly extended; it shall include all main mechanisms (symbolic or not) employed by humans to infer and to make decisions (even "right-hemisphere based" processes, as educated guess, intuition or gambling); b) applied, depending on the sub-field; such mechanisms should be replicated - as "omomorph", as adequate (not as possible!) - in *agent decision making schemata*. If all of them would reach the elegance and dependability of logic, it would be nice, but let it be yet a kind of "princess lointaine", because in real-world systems most concepts involved tend to become blurred. For instance, even metalogic is now nuanced: *soundness* remains crucial (still - apart from time-critical applications - it can be circumvented through revisable reasoning); *completeness* is more negotiable (the oversimplified solution: "otherwise, nothing happens").
■ **"More time for agents".** Nowadays, any software piece unable to interact efficiently with unpredictable environments (humans included) and with its peers is hardly useful outside toy-problems. That

means: parallelism, temporal dimension, non-determinism, reactivity. Corollary: any such program entity has to be implemented as *execution thread* (atomic, sequential, asynchronous and dynamic) [3]. To develop into an agent, the thread needs also non-trivial *informational* and *motivational* components. (However, the "dynamic component" is a treble confusing term: a) it is not a component but the very agent nature; b) the "sense of time" refers to much more than activity - e.g., "waiting" is rather inactivity; c) "dynamic activity" sounds pleonastic from any stance.).

■ **No "start" and no "synchronous agents".** If for e-commerce, it is conceivable to consider that the entire world restarts with each transaction, for process control (even for discrete manufacturing) such eternal re-birth is practically excluded. Moreover, it is against the very spirit of: a) the (still dominant) "client-server" paradigm (the tailor is not spawned every time a client needs new clothes); b) real-time software engineering (to react timely to environment stimuli, the thread must exist to handle the interrupt); c) agency itself: the basic feature of autonomy (implying asynchronous behaviour) is endangered. Luckily, current timers permit a "fine-grain universal metronome", avoiding the costly implication: "asynchronously executing agents → temporal logic of the reals". Thus, "asynchronously executing agents" should be perceived as pleonasm, despite their logic is still based upon a discrete model of time, with both infinite past and future. (In real-world MAS, there is no "Big-Bang".)

■ **No "negative introspection".** Unable to comment upon the advantages of ideal doxastic logics outside large-scale MAS, the authors feel that positive introspection is highly desirable but that assuming the negative one is ineffective for both agents and humans. Thus, if it makes sense and simplifies the features, maybe **KD4**, not **KD45**.

■ **No more certitude. Less checking.** Until agent logics offer mechanisms to deal with uncertainty, at least, in simple expressions, the "ugly chasm" separating formal theory and practical system development [9] cannot be avoided. Just a plain example of a badly needed such mechanism: exception handling. Even primeval animals move "algorithmically" ("*if* gap *then* get round, *else* go on") only a few steps, in very hostile environments. Moreover, reaction to stimuli cannot mean perpetual looking for the stimulus. (Instead, the stimulus causes an interrupt that can be treated as exception.) The cardinal hindrance stems not from logic, but from the mechanisms employed: neither nature, nor technology can afford in the long run mechanisms involving large amount of testing because they are too time-consuming tools: "*if* temperature $>$ n ^{o}C *then* alarm". Thus, the main problem is not the semantics of *"unless"*, but the repeated checking of *"if"*. From this angle, the semantics of *"unless"* in Reiter's default logic would be more tempting if it would be rather diachronic than synchronic (a bird *is* or *is not* a penguin but will never *become* one). However, a kind of *M* operator meaning roughly "while no alarm is heard it is consistent to believe that nothing happened". Indeed, the agent is condemned to be a risk-taker, *hearing* (reactively) the environment, not *listening* (proactively) to it: the agent stops performing a task only if he hears the alarm bell. The point is that this *"if"* belongs to the metalanguage and does not involve thermometer reading! Perhaps a non-monotonic logic with "Reiter-*unless*" inserted in a temporal logic with "Fisher- *unless*" is what designers dream of. (Since dreams are forward-thinking, maybe more: a graphical "flowchart-like" symbol of this *M* shall be understood by an interpreter of an "AOSE-ML" -without "object legacy" - that can create code for defining, raising, propagating, and handling exceptions.

5 Down to Ants: Synergy, Stigmergy, AND Symbols

Since as regards stigmergic coordination the research was recently summarised in [7], [8], [13] and the current results are presented in [7], here, only the approach and some relevant aspects of achieving synergy through grafting symbolic processing onto sub-symbolic systems are emphasised. The AND written in capitals emphasises the similarity with the synonymous boolean operator, i.e. synergy is searched for in all possible combinations.

The MAS that relies on sub-symbolic processing more than any other is the biologically inspired *Ant System* (AS) where the sub-symbolic echelon is represented by the *pheromones* in such a way that global

information is available locally. Moreover, this system is not only sub-symbolic by itself but it also manifests *autopoiesis* (it emerges subsymbolic) and the trouble to understand what is in fact going on at system level, is less upsetting than in the case of more familiar sub-symbolic paradigms (as artificial neural networks or evolutionary algorithms) since ant behaviour is easier to follow due to its simplicity.
The stigmergy related to MAS, "describes a form of asynchronous interaction and information exchange between agents mediated by an 'active' environment", or "the production of certain behaviour in agents as a consequence of the effects produced in the local environment by previous behaviour". In this context: "the agents are simple, reactive, and unaware of other agents or of the emerging complex activities of the agent society; the environment is an important mechanism to guide activities of these agents and to accumulate information about ongoing activities of the whole agent society" [13].
Whereas in [2], [10], [14], the approach was mainly based on self-organization, the approach is an alternative one by obtaining synergy through adding symbolic processing (firstly adapting the environment and secondly instituting limited central coordination). As shown in [7], the AS manifests a threshold and it depends on problem type and complexity; the same solution quality can be obtained with fewer ants than used in common benchmarks, saving thus at least one order of magnitude of processing time.
Details can be found in [13] (improvements to conventional EAS), [8] (motivation, approach and new perspective), and [7] (experimental results about moving the threshold - in fact modifying the sigmoid function to improve efficiency). Possible scientific openings - e.g. whether in real-life problems there are instances when "many starts from four" - can be found also in [7].

6 Conclusions: Beliefs, Desires, Intentions

The conclusions are presented within the BDI frame not just to keep up the atmosphere, but because: a) the conclusions are far from being apodictic and the logics preferred for MAS are doxastic; b) using the meanings given by Smets, the belief functions have rather dispersed values, and the plausibility functions have quite low values for Section 4 and some assertions of Section 3; c) the largest part of Section 3 is actually a gathering of desires; d) intentions is more humble than "future work"; d) if we intend to interact keener with agents, we have to make steps towards common ontologies - preferably based on success stories.
Beliefs:

- Despite the fall of conventional algorithms and the fast rise of sub-symbolic paradigms, symbolic processing is unavoidable in AOSE and agent logics become necessary even outside large-scale systems.
- An essential problem in designing agents is implementing their *reactivity*; main cause: current development environments admit rather very poor exception handling.
- Even MAS based on the most radical sub-symbolic paradigm (stigmergy being "a-symbolic" par excellence), become more effective grafting upon symbolic processing.
- Taking into account the increasing weight of MAS acting as man-machine systems, the anthropocentric perspective requires that human-agent communication should be the model for agent-agent communication.
- Although the brains-surrogate of current agents is still primitive, it shall have two hemispheres, as human do. The left hemisphere, where logic is king, is designed predominantly to implement pro-activeness, whereas the right one, as realm of its instincts, emerges sub-symbolically, and is the main source of reactivity (again, similar to humans).

Desires: They are addressed to future agent logics, from an outsider (but outspoken AOSE) perspective:

- Tackle neglected problems common to all kinds of agent-based systems (dwarfs and trolls welcomed).
- Give us sectorial solutions. They are just fine to begin with. Completeness - in its polysemy - can follow. (If the MAS is sound, nobody minds if agents manifest a bit of schizophrenia.)
- Don't give us sectorial approaches. They are less applicable (e.g., time without uncertainty or vice versa).
- Let MAS be lasting, even if some agents are mortal.
- Don't condemn MAS to act synchronously. Both environment and users are too capricious to accept it. (Instead, we promise to be happy with discrete time.)
- Don't sentence us to perpetual testing. To rephrase Dijkstra: (the condition in) *if* is harmful. (Allow us to handle exceptions, and we promise not to exaggerate eliminating all "iffs".)
- Help us pass the mental Rubicon separating objects from agents. (No agent is fond of being considered "intelligent and responsive like an object".)

Intentions:

- As regards stimergic coordination, the intentions are those states in [7]: for short, increasing "stigsynergy".
- Showing how agent reactivity can be significantly improved, through exception-driven multimodal interfaces.
- Trying dialectics as inference mechanism for negotiation strategies used by e-commerce agents.

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References

[1] "AgentLink Roadmap: Overview and Consultation Report", *AgentLink III. Agent based computing*, University of Southampton, 2004.

[2] Banzhaf, W., "Self-organizing Systems", *Encyclopedia of Physical Science and Technology*, Academic Press, New York, **14**, pp. 589-598, 2002.

[3] Bărbat, B.E., "Sisteme inteligente orientate spre agent", *Ed. Academiei Române*, Bucureşti, 467 pages, 2002.

[4] Bărbat, B.E., "The Avatar - A Pseudo-Human Extending the Genuine One", *The good, the bad and the irrelevant: The user and the future of information and communication technologies*, (L. Haddon et al, Eds.), pp. 38-42, Media Lab/University of Art and Design, Helsinki, 2003.

[5] Bărbat, B.E., "The Impact of Broad-Band Communication upon HMI Language(s). (Chapter 7.) Communicating in the world of humans and ICTs. (Chapter 8.)", *COST Action 269. e-Citizens in the Arena of Social and Political Communication*, (L. Fortunati, Ed.), pp. 113-142, EUR21803, Office for Official Publications of the European Communities, Luxembourg, 2005.

[6] Bărbat, B.E., N. Bulz, "E-World and Real World. From Analysing Concepts towards Integrating Approaches", *Proc. of the WOSC 13th International Congress of Cybernetics and Systems*, University of Maribor in cooperation with Encyclopaedia of Life Support Systems, **1**, pp. 47-57, 2005.

[7] Bărbat, B.E., S.C. Negulescu, C.B. Zamfirescu, "Human-Driven Stigmergic Control. Moving the Threshold", *Proc. of the 17th IMACS World Congress (Scientific Computation, Applied Mathematics and Simulation)*, Paris, July 11-15, 2005.

[8] Bărbat, B.E., C.B. Zamfirescu, S.C. Negulescu, "The Best from Ants and Humans: Synergy in Agent-Based Systems", *Studies in Informatics and Control Journal*, **13**, 1, 47-59, 2004.

[9] Fisher, M., "Temporal Development Methods for Agent-Based Systems", *Autonomous Agents and Multi-Agent Systems*, **10**, pp. 41-66, Springer Science + Business Media Inc., 2005.

[10] Knyazeva, H., Haken, H., "Synergetics of Human Creativity. Dynamics, Synergetics, Autonomous Agents", *ANonlinear Systems Approaches to Cognitive Psychology and Cognitive Science Singapore: World Scientific*, pp. 64-79, 1999.

[11] Luck, M., McBurney, P., Priest, C., "A Manifesto for Agent Technology: Towards Next Generation Computing", *Autonomous Agents and Multi-Agent Systems*, **9**, 203-252, Kluwer Academic Publishers, 2004.

[12] Moisil, Gr.C., "Lecţii despre logica raţionamentului nuanţat", *Ed. Ştiinţifică şi enciclopedică*, Bucureşti, 1975.

[13] Negulescu, S.C., Bărbat, B.E., "Enhancing the Effectiveness of Simple Multi-Agent Systems through Stigmergic Coordination", *Fourth International ICSC Symp. on ENGINEERING OF INTELLIGENT SYSTEMS (EIS 2004)*, ICSC-NAISO Academic Press Canada, 149 (Abstract; full paper on CD-ROM enclosed), 2004.

[14] Parunak, H.V.D., Brueckner, S., John A. Sauter, Matthews, R., "Global Convergence of Local Agent Behavior", *Submitted to The Fourth International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS'05)*, 2005, Available at http://www.erim.org/ vparunak/ AAMAS05Converge.pdf.

[15] Zambonelli, F., Omicini, A., "Challenges and Research Directions in Agent-Oriented Software Engineering", *Autonomous Agents and Multi-Agent Systems*, **9**, 253-283, Kluwer Academic Publishers, 2004.

Boldur E. Bărbat
"Lucian Blaga" University of Sibiu
Faculty of Science
Address: 5-7, Ion Raţiu Street, Sibiu, 550012, România
E-mail: bbarbat@gmail.com

Sorin C. Negulescu
"Lucian Blaga" University of Sibiu
Faculty of Engineering
Address: 4, Emil Cioran Street, Sibiu, 550025, România
E-mail: sorin_negulescu@yahoo.com

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A Programming Perspective of the Membrane Systems

Gabriel Ciobanu

Abstract: We present an operational semantics of the membrane systems, using an appropriate notion of configurations and sets of inference rules corresponding to the three stages of an evolution step in membrane systems: maximal parallel rewriting step, parallel communication of objects through membranes, and parallel membrane dissolving.
We define various arithmetical operations over multisets in the framework of membrane systems, indicating their complexity and presenting the membrane systems which implement the arithmetic operations.
Finally we discuss and compare various sequential and parallel software simulators of the membrane systems, emphasizing their specific features.
Keywords: membrane systems, operational semantics, arithmetical operations over multisets.

1 Membrane Systems

Membrane systems represent a computational model inspired by cell compartments and molecular membranes. Essentially, such a system is composed of various compartments, each compartment with a different task, and all of them working simultaneously to accomplish a more general task of the whole system. A detailed description of the membrane systems (also called P systems) can be found in [17]. A *membrane system* consists of a hierarchy of membranes that do not intersect, with a distinguishable membrane, called the *skin membrane*, surrounding them all. The membranes produce a delimitation between *regions*. For each membrane there is a unique associated region. Regions contain multisets of *objects*, *evolution rules* and possibly other membranes. Only rules in a region delimited by a membrane act on the objects in that region. The multiset of objects from a region corresponds to the "chemicals swimming in the solution in the cell compartment", while the rules correspond to the "chemical reactions possible in the same compartment". Graphically, a membrane structure is represented by a Venn diagram in which two sets can be either disjoint, or one is a subset of the other. More details (concepts, results) and several variants of membrane systems are presented in [17].

A *P system* consists of several membranes that do not intersect, and a *skin membrane*, surrounding them all. The membranes delimit *regions*, and contain multisets of *objects*, as well as *evolution rules*. Each membrane has a unique associated region. The space outside the skin membrane is called the *outer region* (or the environment). Because of the one-to-one correspondence between the membranes and the regions, we usually use the word membrane instead of region. Only rules in a region delimited by a membrane act on the objects in that region. Moreover, the rules must contain target indications, specifying the membrane where objects are sent after applying the rule. The objects can either remain in the same region, or pass through membranes in two directions: they can be sent *out* of the membrane which delimits a region from outside, or can be sent *in* one of the membranes which delimit a region from inside, precisely identified by its label. The membranes can also be *dissolved*. When such an action takes place, all the objects of the dissolved membrane remain free in the membrane placed immediately outside, but the evolution rules of the dissolved membranes are lost. The skin membrane is never dissolved. The application of evolution rules is done in parallel, and it is eventually regulated by *priority* relationships between rules. A *P system* of degree m is a structure $\Pi = (O, \mu, w_1, \ldots, w_m, (R_1, \rho_1), \ldots, (R_m, \rho_m), i_o)$, where:

(i) O is an alphabet of objects, and μ is a membrane structure;

Selected from ICCCC 2006 (invited paper)

(ii) w_i are the initial multisets over O associated with the regions defined by μ;

(iii) R_i are finite sets of evolution rules over O associated with the membranes, of typical form $u \rightarrow v$, with u a multiset over O and v a multiset containing paired symbols (messages) of the form $(c, here)$, (c, in_j), (c, out) and the dissolving symbol δ;

(iv) ρ_i is a partial order relation over R_i, specifying a *priority* relation among the rules: $(r_1, r_2) \in \rho_i$ iff $r_1 > r_2$ (i.e., r_1 has a higher priority than r_2);

(v) i_0 is either a number between 1 and m specifying the *output* membrane of Π, or it is equal to 0 indicating that the output is the outer region.

Since the skin is not allowed to be dissolved, we consider that the rules of the skin do not involve δ. These are the *general P systems*, or *transition P systems*; many other variants and classes were introduced [17].

The existing results regarding the P systems refer mainly to their computation power and complexity, namely to their characterization of Turing computability (universality is obtained even with a small number of membranes, and with rather simple rules), and the polynomial solutions to NP-complete problems by using an exponential workspace created in a "biological way" (e.g., membrane division, string replication). Other types of formal results are given by normal forms, hierarchies, connections with various formalisms.

In this paper we refer to some "programming" aspects of the membrane systems. We first present an operational semantics of the P systems, together with some correctness results. Then we define several arithmetical operations in membrane systems using a natural encoding of numbers. Finally some software simulators of the membrane systems are presented.

2 Structural Operational Semantics

Membrane systems provide an abstract model for parallel systems, and a suitable framework for distributed and parallel algorithms [7]. For each abstract model, theory of programming introduces various paradigms and uses different notions of computations. Turing machines and register machines are related to imperative programming, and λ-calculus is related to functional programming. It is natural to look at the membrane systems from the point of view of programming theory. This means that we define an abstract syntax, and an operational semantics of the membranes systems. The operational semantics of the membrane systems is given in a big-step style, each step representing the collection of parallel steps due to the maximal parallelism principle. A computation is regarded as a sequence of parallel application of rules in various membranes, followed by a communication step and a dissolving step.

The membrane structure and the multisets in Π determine a configuration of the system. We can pass from a configuration to another one by using the evolution rules. This is done in parallel: all objects, from all membranes, which can be the subject of local evolution rules, as prescribed by the priority relation, should evolve concurrently. Since the right hand side of a rule consists only of messages, an object introduced by a rule cannot evolve at the same step by means of another rule. The use of a rule $u \rightarrow v$ in a region with a multiset w means to subtract the multiset identified by u from w, and then to add the objects of v according to the form of the rule. If an object appears in v in the form $(c, here)$, then it remains in the same region. If we have (c, in_j), then c is introduced in the child membrane with the label j; if a child membrane with the label j does not exist, then the rule cannot be applied. If we have (c, out), then c is introduced in the membrane placed immediately outside the region of the rule $u \rightarrow v$. If the special symbol δ appears in v, then the membrane which delimits the region is dissolved; in this way, all the objects in this region become elements of the region placed immediately outside, while the rules of the dissolved membrane are removed.

Let O be a finite alphabet of objects organized as a free commutative monoid O_c^*, whose elements are called *multisets*. Formally, the set of *membranes for a system* Π, denoted by $\mathcal{M}(\Pi)$, and *the membrane structure* are inductively defined as follows:

- if L is a label, and w is a multiset over $O \cup (O_c^* \times \{here\}) \cup (O_c^+ \times \{out\}) \cup \{\delta\}$, then $\langle L \,|\, w \rangle \in \mathcal{M}(\Pi)$; $\langle L \,|\, w \rangle$ is called *simple (or elementary) membrane*, and it has the structure $\langle\rangle$;
- if $M_1, \ldots, M_n \in \mathcal{M}(\Pi)$ with $n \geq 1$, the structure of M_i is μ_i for all $i \in [n]$, L is a label, w is a multiset over $O \cup (O_c^* \times \{here\}) \cup (O_c^+ \times \{out\}) \cup (O_c^+ \times \{in_{L(M_j)} | j \in [n]\}) \cup \{\delta\}$, then $\langle L \,|\, w; M_1, \ldots, M_n \rangle \in \mathcal{M}(\Pi)$; $\langle L \,|\, w; M_1, \ldots, M_n \rangle$ is called *a composite membrane*, and it has the structure $\langle \mu_1, \ldots, \mu_n \rangle$.

A finite set of membranes is usually written as $M_1, \ldots, M_n$. We denote by $\mathcal{M}^+(\Pi)$ the set of non-empty finite sets of membranes. The union of two multisets of membranes $M_+ = M_1, \ldots, M_m$ and $N_+ = N_1, \ldots, N_n$ is written as $M_+, N_+ = M_1, \ldots, M_m, N_1, \ldots, N_n$. An element from $\mathcal{M}^+(\Pi)$ is either a membrane, or a set of sibling membranes.

A *committed configuration* for a membrane system Π is a skin membrane which has no messages and no dissolving symbol δ, i.e., the multisets of all regions are elements in O_c^*. We denote by $\mathcal{C}(\Pi)$ the set of committed configurations for Π, and it is a proper subset of $\mathcal{M}^+(\Pi)$. We have $C \in \mathcal{C}(\Pi)$ iff C is a skin membrane of Π and $w(M)$ is a multiset over O for each membrane M in $\mathcal{C}$.

An *intermediate configuration* is a skin membrane in which we have messages or the dissolving symbol δ. The set of intermediate configurations is denoted by $\mathcal{C}^{\#}(\Pi)$. We have $C \in \mathcal{C}^{\#}(\Pi)$ iff C is a skin membrane of Π such that there is a membrane M in C with $w(M) = w'w''$, $w' \in (Msg(O) \cup \{\delta\})_c^+$, and $w'' \in O_c^*$. By $Msg(O)$ we denote the set $(O^* \times \{here\}) \cup (O^+ \times \{out\}) \cup (O^+ \times \{in_L(M)\})$.

A *configuration* is either a committed configuration or an intermediate configuration. Each membrane system has an initial committed configuration which is characterized by the initial multiset of objects for each membrane and the initial membrane structure of the system.

Each P system has an initial configuration which is characterized by the initial multiset of objects for each membrane and the initial membrane structure of the system. For two configurations C_1 and C_2 of Π, we say that there is a *transition* from C_1 to C_2, and write $C_1 \Rightarrow C_2$, if the following *steps* are executed in the given order:

1. *maximal parallel rewriting step*, consisting of non-deterministically assigning objects to evolution rules in every membrane and executing the rules in a maximal parallel manner;

2. *parallel communication of objects through membranes*, consisting in sending existing messages;

3. *parallel membrane dissolving*, consisting in dissolving the membranes containing δ.

The last two steps take place only if there are messages or δ symbols resulted from the first step, respectively. If the first step is not possible, consequently neither the other two steps, then we say that the system has reached a *halting configuration*. An operational semantics of the P systems, considering each of the three steps, is presented in [2]. We mention here the main results.

We can pass from a configuration to another one by using the evolution rules. This is done in parallel: all objects from all membranes evolve simultaneously according to the evolution rules and their priority relation. The rules of a membrane are using its current objects as much as this is possible in a parallel and non-deterministic way. However, an object produced by a rule cannot evolve at the same step as source of another rule. The use of a rule $u \to v$ in a region with a multiset w has as effect the subtraction of the multiset identified by u from w, followed by the addition of the multiset identified by v.

We denote the *maximal parallel rewriting* on membranes by $\stackrel{mpr}{\Longrightarrow}$ and by $\stackrel{mpr}{\Longrightarrow}_L$ the maximal parallel rewriting over the multisets of objects of the membrane labelled by L (we omit the label whenever it is clear from the context). The rules defining the maximal parallel rewriting use two predicates regarding mpr-irreducibility and (L, w)-consistency.

Proposition 1. Let Π be a membrane system. If $C \in \mathcal{C}(\Pi)$ and $C' \in \mathcal{C}^{\#}(\Pi)$ such that $C \stackrel{mpr}{\Longrightarrow} C'$, then C' is mpr-irreducible.

We denote the *parallel communication relation* by $\stackrel{tar}{\Longrightarrow}$. The rules defining the parallel communication relation use a predicate expressing tar-irreducibility.

Proposition 2. Let Π be a P system. If $C \in \mathcal{C}^{\#}(\Pi)$ with messages and $C \stackrel{tar}{\Longrightarrow} C'$, then C' is tar-irreducible.

We denote the *parallel dissolving relation* by $\stackrel{\delta}{\Longrightarrow}$. The rules defining the parallel dissolving relation use a predicate expressing δ-irreducibility. We note that $C \in \mathcal{C}(\Pi)$ iff C is tar-irreducible and δ-irreducible.

Proposition 3. Let Π be a P system. If $C \in \mathcal{C}^{\#}(\Pi)$ is tar-irreducible and $C \stackrel{\delta}{\Longrightarrow} C'$, then C' is δ-irreducible.

According to the standard description in membrane computing, a *transition step* between two configurations $C, C' \in \mathcal{C}(\Pi)$ is given by: $C \Rightarrow C'$ iff C and C' are related by one of the following relations:

either $C \stackrel{mpr}{\Longrightarrow}; \stackrel{tar}{\Longrightarrow} C'$, or $C \stackrel{mpr}{\Longrightarrow}; \stackrel{\delta}{\Longrightarrow} C'$, or $C \stackrel{mpr}{\Longrightarrow}; \stackrel{tar}{\Longrightarrow}; \stackrel{\delta}{\Longrightarrow} C'$.

The three alternatives in defining $C \Rightarrow C'$ are given by the existence of messages and dissolving symbols along the system evolution. Starting from a configuration without messages and dissolving symbols, we apply the "mpr" rules and get an intermediate configuration which is mpr-irreducible; if we have messages, then we apply the "tar" rules and get an intermediate configuration which is tar-irreducible; if we have dissolving symbols, then we apply the dissolving rules and get a configuration which is δ-irreducible. If the final configuration has no messages or dissolving symbols, then we say that the transition relation $\Rightarrow$ is well-defined as an evolution between the initial and final configurations.

Proposition 4. The relation $\Rightarrow$ is well-defined over the entire set $\mathcal{C}(\Pi)$ of configurations.

Examples of inference trees, as well as the proofs of the results are presented in [2].

Operational semantics provides us with a formal way to find out which transitions are possible for the current configuration of a membrane system. Given an operational semantics, we can derive easily an interpreter for membrane systems, as well as the basis for the definition of certain equivalences and congruences between membrane systems. Moreover, given an operational semantics, we can reason about the rules defining the semantics. A notion of bisimulation can be defined (see [2]), and the bisimulation relation allows to compare the evolution behaviour of two membrane systems.

3 Arithmetical Operations in Membrane Systems

The problem of number encoding using multisets is interesting and complex. The first paper on the encodings and arithmetical operations in membrane systems is [5]. In [5] we present several combinatorial results and some encodings of numbers using multisets. Here we present some arithmetical operations over numbers encoded by a simple and natural encoding (each object of a membrane represents a unit, and we use n objects to represent the number n). We indicate the complexity of some arithmetical operations, and build the membrane systems which implement the arithmetic operations over the encoded numbers.

Addition
Time complexity: $O(1)$

$$\begin{aligned}\Pi &= (V,\mu,w_0,(R_0,\emptyset),0),\\ V &= \{a,b\},\\ \mu &= [_0]_0,\\ w_0 &= a^n b^m,\\ R_0 &= \{b \to a\}.\end{aligned}$$

Addition is trivial; we consider n objects a and m objects b. The rule $b \to a$ says that an object b is transformed in one object a. Such a rule is applied in parallel as many times as possible. Consequently, all objects b are erased. The remaining number of objects a represents the addition $n+m$.

Subtraction
Time complexity: $O(1)$

$$\begin{aligned}\Pi &= (V,\mu,w_0,(R_0,\emptyset),0),\\ V &= \{a,b\},\\ \mu &= [_0]_0,\\ w_0 &= a^n b^m,\\ R_0 &= \{ab \to \lambda\}.\end{aligned}$$

Subtraction is described in the following way: given n objects a and m objects b, a rule $ab \to \lambda$ says that one object a and one object b are deleted (this is represented by the empty symbol λ). Consequently, all the pairs ab are erased. The remaining number of objects represents the difference between n and m.

Multiplication without promoters
Time complexity: $O(n \cdot m)$

The object is a promoter for a rule if the rule can be applied only in the presence of object. Figure 1 presents a P system Π_1 without promoters for multiplication of n (objects a) by m (objects b), the result being the number of objects d in membrane 0. In this P system we use the priority relation between rules; for instance $bv \to dev$ has a higher priority than $av \to u$, meaning the second rule is applied only when the first one cannot be applied anymore. Initially only the rule $au \to v$ can be applied, generating an object v which activates the rule $bv \to dev$ m times, and then $av \to u$. Now $eu \to dbu$ is applied m times, followed by $au \to v$. The procedure is repeated until no object a is present within the membrane. We note that each time when one object a is consumed, then m objects d are generated.

$$\begin{aligned}\Pi_1 &= (V,\mu,w_0,(R_0,\rho_0),0),\\ V &= \{a,b,e,v,u\},\\ \mu &= [_0]_0,\\ w_0 &= a^n b^m u,\\ R_0 &= \{r_1 : au \to v, r_2 : bv \to dev, r_3 : av \to u, r_4 : eu \to dbu\},\\ \rho_0 &= \{r_2 > r_1, r_4 > r_3\}.\end{aligned}$$

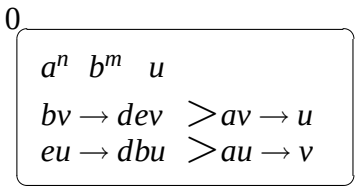

Figure 1: Multiplier without promoters

Multiplication with promoters
Time complexity: $O(n)$

Figure 2 presents a P system Π_2 with promoters for multiplication of n (objects a) by m (objects b), the result being the number of objects d in membrane 0. In this P system we use rules with priority and with promoters. The object a is a promoter in the rule $b \to bd|_a$, i.e., this rule can only be applied in the presence of object a. The available m objects b are used in order to apply m times the rule $b \to bd|_a$ in parallel; based on the priority relation and the availability of a objects (except one a as promoter), the rule $au \to u$ is applied in the same time. The priority relation is motivated because the promoter a is a resource for which the rules $b \to bd|_a$and $au \to u$ are competing. The procedure is repeated until no object a is present within the membrane. We note that each time when one object a is consumed, then m objects d are generated.

$$\begin{aligned}
\Pi_2 &= (V, \mu, w_0, (R_0, \rho_0), 0),\\
V &= \{a, b, u\},\\
\mu &= [_0]_0,\\
w_0 &= a^n b^m u,\\
R_0 &= \{r_1 : b \to bd|_a, r_2 : au \to u\},\\
\rho_0 &= \{r_1 > r_2\}.
\end{aligned}$$

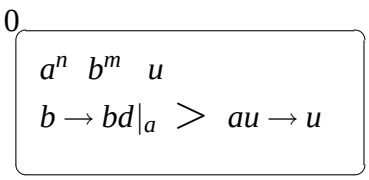

Figure 2: Multiplier with promoters

The membrane systems for multiplication differ from others presented in the literature [17] because they do not have exponential space complexity, and do not require active membranes. As a particular case, it would be quite easy to compute n^2 by just placing the same number n of objects a and b. Another interesting feature is that the computation may continue after reaching a certain result, and so the system acts as a P transducer [12]. Thus if initially there are n (objects a) and m (objects b), the system evolves and produces $n \cdot m$ objects d. Afterwards, the user can inject more objects a and the system continues the computation obtaining the same result as if the objects a are present from the beginning. For example, if the user wishes to compute $(n+k) \cdot m$, it is enough to inject k objects a at any point of the computation. Therefore this example emphasizes the asynchronous feature and a certain degree of reusability and robustness.

Division

We implement division as repeated subtraction. We compute the quotient and the remainder of n_2 (objects a in membrane 1) divided by n_1 (objects a in membrane 0) in the same P system evolution. The evolution starts in the outer membrane by applying the rule $a \rightarrow b(v, in_1)$. The (v, in_1) notation means that the object v is injected into the child membrane 1. Therefore the rule $a \rightarrow b(v, in_1)$ is applied $n_1$times converting the objects a into objects b, and object v is injected in the inner membrane 1. The evolution continues with a subtraction step in the inner membrane, with the rule $av \rightarrow e$ applied n_1 times whenever possible.

$$
\begin{aligned}
\Pi &= (V, \mu, w_0, w_1, (R_0, \rho_0), (R_1, \rho_1), 0), \\
V &= \{a, b, b', c, s, u, v\}, \\
\mu &= [_0[_1]_1]_0, \\
w_0 &= a^{n_1}s, \\
w_1 &= a^{n_2}s, \\
R_0 &= \{a \rightarrow b(v, in_1), b' \rightarrow a, r_1 : bu \rightarrow b'|_{\neg v}, r_2 : u \rightarrow \delta|_{\neg v}, r_3 : csu \rightarrow u|_v\}, \\
\rho_0 &= \{r_1 > r_2, r_2 > r_3\}, \\
R_1 &= \{r_1 : av \rightarrow e, r_2 : v \rightarrow (v, out), \\
&\quad\ r_3 : es \rightarrow s(u, out)(c, out), r_4 : e \rightarrow (u, out)\}, \\
\rho_1 &= \{r_1 > r_2, r_2 > r_3, r_3 > r_4\}.
\end{aligned}
$$

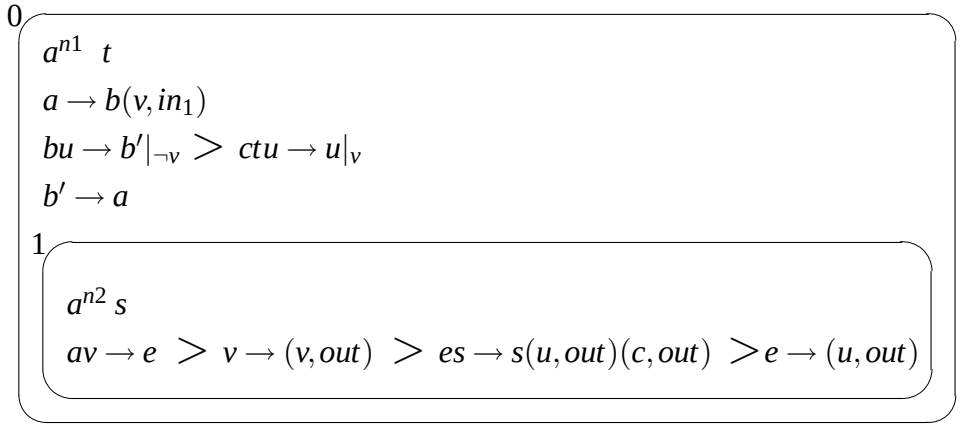

Figure 3: P system for division

Two cases are distinguished in the inner membrane:

- If there are more objects a than objects v, only the rules $es \rightarrow s(u, out)(c, out)$ and $e \rightarrow (u, out)$ are applicable. Rule $es \rightarrow s(u, out)(c, out)$ sends out to membrane 0 a single c (restricted by the existence of a single s into this membrane) for each subtraction step. The number of objects c represents the quotient. On the other hand, both rules send out n_1 objects u (equal to the number of objects e). The evolution continues in the outer membrane by applying $bu \rightarrow b'|_{\neg v}$ of $n_1$times, meaning the objects b are converted into objects b' by consuming the objects u only in the absence of v ($|_{\neg v}$ denotes an inhibitor having an effect opposite to that of a promoter). Then the rule $b' \rightarrow a$ produces the necessary objects a to repeat the entire procedure.

- When there are less objects a than objects v in the inner membrane we get a division remainder. After applying the rule $av \rightarrow e$, the remaining objects v activate the rule $v \rightarrow (v, out)$. Therefore all these objects v are sent out to the parent membrane 0, and the rules $es \rightarrow s(u, out)(c, out)$ and $e \rightarrow (u, out)$ are applied. Due to the fact that we have objects v in membrane 0, the rule $bu \rightarrow b'|_{\neg v}$ cannot be applied. Since n_2 is not divisible by n_1, the number of the left objects u in membrane 0 represents the remainder of the division. A final cleanup is required in this case, because an object c is sent out even if we have not a "complete" subtraction step; the rule $ctu \rightarrow u|_v$ removes that extra c from membrane 0 in the presence of v. This rule is applied only once because we have a unique t in this membrane.

The natural encoding is easy to understand and work with. However it has the disadvantage that the membranes can contain a very large number of objects when working with very large numbers. We introduce and study the most compact encoding using two object types (binary case) in [5], where we present other P systems implementing the arithmetical operations on numbers encoded using the binary cases of the most compact encoding. We use a web-based simulator available at `http://psystems.ieat.ro` to implement the arithmetical operations, and test each P system.

4 Software Implementations

Several programming paradigms and programming languages have been selected for implementing membrane systems simulators: Lisp, Haskell, MzScheme (as functional programming languages) Prolog, CLIPS (as declarative languages), C, C++, Java (as imperative and object-oriented languages). The user interface can be designed separately from the engine performing the evolution, and it is possible to use different programming languages able to communicate with each other. Each programming paradigm, each programming language has advantages and disadvantages.

Transition membrane systems and deterministic membrane systems with active membranes are simulated in Prolog [14]; they are used to solve NP-complete problems as SAT, VALIDITY, Subset Sum, Knapsack, and partition problems. Sevilla carpets describing the complexity of a membrane system computation [11] are used as a graphical representation for a partition problem in [20].

Membrane systems with active membranes, input membrane and external output are simulated in CLIPS and used to solve NP-complete problems in [18]. The simulator presented in [18] allows to observe the evolution of the systems with active membranes based on production system techniques. The set of rules and the configurations in each step of the evolution are expressed as facts in a knowledge base.

Rewriting membrane systems and membrane systems with symport/antiport rules are described as executable specifications in MAUDE in [1]. The advantage of this approach is that it uses the existing tools of Maude, and it is used to verify the temporal properties of the membrane systems expressed in linear temporal logic.

A more complex simulator (written in Visual C++) for membrane systems with active membranes and catalytic membrane systems is presented in [10]. It provides a graphical simulator, interactive definition, visualization of a defined membrane system, a scalable graphical representation of the computation, and step-by-step observations of the membrane system behaviour. The simulation of these membrane systems has to deal with the potential growth of the membrane structure and adapt dynamically the topology of the configurations depending if some membranes are added or deleted. Polynomial-time solutions to **NP**-complete problems via membrane systems can be reached trading time by space. This is done by producing (via membrane division) an exponential amount of membranes that can work in parallel.

In [10] it is presented a software implementation which provides a graphical simulation for two variants of membrane systems: for the initial version of catalytic hierarchical cell systems, and for membrane

systems with active membranes. Its main functions are given by an interactive definition of a membrane system, a visualization of a defined membrane system, a graphical representation of the computation and final result, and saving and (re)loading a defined membrane system. The application is implemented in Microsoft Visual C++ using MFC classes. For a scalable graphical representation, the Microsoft DirectX technology is used. One of the main features of this technology is that the size of each component of the graphical representation is adjusted according to the number of membranes of the system. The system is presented to the user with a graphical interface where the main screen is divided into two windows: The left window gives a tree representation of the membrane system including objects and membranes. The right window provides a graphical representation of the membrane system given by Venn-like diagrams. A menu allows the specification of a membrane system for adding new objects, membranes, rules and priorities. By using the functions *Start*, *Next* and *Stop*, the users can observe the system evolution step-by-step.

By simulating parallelism and nondeterminism on a sequential machine one can lose the power and attractiveness of membrane system computing. Parallel and cluster implementation for transition membrane systems in C++ and MPI are reported in [8] and [9]. The rules are implemented as threads. At the initialization phase, one thread is created for each rule. Rule applications are performed in terms of rounds. To synchronize each thread (rule) within the system, two barriers implemented as mutexes are associated with the thread. At the beginning of each round, the barrier that the rule thread is waiting on is released by the primary controlling thread. After the rule application is done, the thread waits for the second barrier, and the primary thread locks the first barrier. Since each rule is modelled as a separate thread, it should have the ability to decide its own applicability in a particular round. Generally speaking, a rule can run when no other rule with higher priority is running, and the resources required are available. When more than one rule can be applied in the same conditions, the simulator picks randomly one among the candidates. With respect to the synchronization and communication, for every membrane, the main communication is done by sending and receiving messages to and from its father and children at the end of every round. With respect to the termination, when the system is no longer active, there is no rule in any membrane that is applicable. When this happens, the designated output membrane prints out the result and the whole system halts. In order to detect if the membrane system halts, each membrane must inform the other membranes about its inactivity. It can do so by sending messages to others, and by using a termination detection algorithm [4].

The implementation was designed for a cluster of computers. It is written in C++ and it makes use of *Message Passing Interface (MPI)* as its communication mechanism. MPI is a standard library developed for writing portable message passing applications, and it is implemented both on shared-memory and on distributed-memory parallel computers. The program was implemented and tested on a Linux cluster at the National University of Singapore; the cluster consisted of 64 dual processor nodes.

The above implementations represent the first generation of membrane systems simulators. The recent developments are related to biological applications, and to a new generation of Web-based simulators. WebPS is an open-source web-enabled simulator for membrane systems [6]. The simulator is based on CLIPS, and it is already available as a Web application. As any Web application, WebPS does not require an installation. It can be used from any machine anywhere in the world, without any previous preparation. A simple and easy to use interface allows the user to supply an XML input both as text and as a file. A friendly way of describing membrane systems is given by an interactive JavaScript-based membrane system designer. The interface provides a high degree of (re)usability during the development and simulation of the membrane systems. The initial screen offers an example, and the user may find useful documentation about the XML schema, the rules, and the query language. The query language helps the user to select the output of the simulation. The simulator is free software, and it offered at `http://psystems.ieat.ro` under the *GNU General Public License*. This allows anyone to contribute with enhancements and error corrections to the code, and possibly develop new interfaces for the C and CLIPS level APIs. These interfaces can be local (graphical or command-line), or yet other

Web-based ones.

In the same paper [6], the authors present an accelerator for parallelization of the existing sequential simulators. This accelerator is used to parallelize an existing CLIPS simulator [18]. The speedup and the efficiency of the resulting parallel implementation are surprisingly close to the ideal ones.

5 Conclusion and Related Work

Structural operational semantics is an approach originally introduced by Plotkin [19] in which the operational semantics of a programming language or a computational model is specified in a logical way, independent of a machine architecture or implementation details, by means of rules that provide an inductive definition based on the elementary structures of the language or model. Structural operational semantics is intuitive and flexible, and it becomes more attractive during the years by the developments presented by Kahn [15] and Milner [16]. Configurations are states of transition systems, and computations consists of sequences of transitions between configurations, and terminating (if it terminates) in a final configuration. We present a structural operational semantics of the membrane systems; the inference rules provide a big-step operational semantics due to the parallel nature of the model. A structural operational semantics of the systems emphasizes also the deductive nature of the membrane computing by describing the transition steps by using a set of inference rules. Considering a set $\mathcal{R}$ of inference rules, we can describe the computation of a membrane system as a deduction tree. In [3] we translate the big-step operational semantics of membrane systems into rewriting logic. By using the rewriting engine Maude [13], we obtain an interpreter for membrane systems, and verify various properties of these systems.

Looking at the membrane systems from the point of view of programming theory, we define an appropriate data representation for P systems, and make the first steps to define an arithmetic unit for these abstract machine inspired by cells. The natural encoding over multisets is very close to biology, and can help to understand some biological mechanisms, improving also some computational models inspired by biology.

We have designed and implemented sequential and parallel software simulators; we present some of them, and compare with other software simulators of the P systems. A web-based implementation is presented in [6].

Acknowledgements

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References

[1] O. Andrei, G. Ciobanu, D. Lucanu. Executable Specifications of the P Systems. In *Membrane Computing WMC5*, LNCS vol.3365, Springer, 127-146, 2005.

[2] O. Andrei, G. Ciobanu, D. Lucanu. Structural Operational Semantics of P Systems. *Proceedings WMC6*, LNCS vol.3850, Springer, 32-49, 2006.

[3] O. Andrei, G. Ciobanu, D. Lucanu. Operational Semantics and Rewriting Logic in Membrane Computing. *Proceedings SOS Workshop* 2005, to appear in *ENTCS*.

[4] H. Attiya, J. Welch, *Distributed Computing: Fundamentals, Simulations and Advanced Topics*. McGraw-Hill, 2000.

[5] C. Bonchiş, G. Ciobanu, C. Izbaşa. Encodings and Arithmetic Operations in Membrane Computing. In Jin-Yi Cai, S. Barry Cooper, Angsheng Li (Eds.): *Theory and Applications of Models of Computation*, LNCS 3959, Springer, 618–627, 2006.

[6] C. Bonchiş, G.Ciobanu, C. Izbaşa, D. Petcu. A Web-based P systems simulator and its parallelization. In C.Calude et al. (Eds.): *Unconventional Computing*, LNCS vol.3699, Springer, 58-69, 2005.

[7] G. Ciobanu. Distributed Algorithms over Communicating Membrane Systems. *Biosystems* vol.70, Elsevier, 123-133, 2003.

[8] G. Ciobanu, R. Desai, A. Kumar. Membrane Systems and Distributed Computing. In *Proceedings WMC3*, LNCS vol.2597, Springer, 187-202, 2003.

[9] G. Ciobanu, W. Guo. P Systems Running on a Cluster of Computers. In *Procedings 4th WMC*, Taragona, LNCS vol.2933, Springer, 123-139, 2004.

[10] G. Ciobanu, D. Paraschiv. P System Software Simulator. *Fundamenta Informaticae* 49, 61-66, 2002.

[11] G. Ciobanu, Gh. Păun, Gh.Ştefănescu. Sevilla Carpets Associated with P Systems. *Report 26/03 Rovira i Virgili University*, Tarragona, 135-140, 2003.

[12] G. Ciobanu, Gh. Păun, Gh. Ştefănescu. P Transducers. *New Generation Computing* **24**, 1–28, 2006.

[13] M. Clavel, F. Durán, S. Eker, P. Lincoln, N. Martí-Oliet, J. Meseguer, J.F. Quesada. Maude: Specification and Programming in Rewriting Logic. *Theoretical Computer Science*, vol.285, 187-243, 2002.

[14] A. Cordon-Franco, M.A. Gutierrez-Naranjo, M.J. Perez-Jimenez, A. Riscos-Nunez, F. Sancho-Caparrini. Implementing in Prolog an Effective Cellular Solution for the Knapsack Problem. In *Proceedings 4th WMC*, Taragona, LNCS vol.2933, Springer, 140-152, 2004.

[15] G. Kahn. *Natural semantics*, Technical Report 601, INRIA Sophia Antipolis, 1987.

[16] R. Milner. Operational and algebraic semantics of concurrent processes. In J. van Leeuwen (Ed.), *Handbook of Theoretical Computer Science* vol.B, 1201-1242, Elsevier Science, 1990.

[17] Gh. Păun. *Membrane Computing. An Introduction*. Springer, 2002.

[18] M.J. Perez-Jimenez, F.J. Romero-Campero. A CLIPS Simulator for Recognizer P Systems with Active Membranes. In *Proceedings 2nd Brainstorming Week on Membrane Computing*, University of Sevilla Tech. Rep 01/2004, 387-413, 2004.

[19] G. Plotkin. Structural operational semantics. *Journal of Logic and Algebraic Programming* vol.60, 17-139, 2004.

[20] A. Riscos-Núñez, *Cellular Programming: Efficient Resolution of Numerical NP-Complete Problems*. PhD Thesis, University of Seville, 2004.

Gabriel Ciobanu
Romanian Academy
Institute of Computer Science
Address: Blvd. Carol I nr.8, Iaşi
E-mail: gabriel@iit.tuiasi.ro

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Pathogen Variability. A Genomic Signal Approach

Paul Dan Cristea

Abstract: The conversion of genomic symbolic sequences into digital signals has been applied for the analysis pathogen variability. Results are given on the variability of Human Immunodeficiency Virus, type 1, subtype F, isolated in Romania, and of the type A avian influenza virus H5N1, for which sequences have been downloaded from GenBank [1]. Nucleotide sequence analysis is corroborated with techniques based on the genomic signal approach to detect pathogen resistance to antiretroviral treatment. In the case of protease (PR) inhibitors, it is found that the treatment induces single nucleotide polimorphisms (SNPs) in specific sites. For moderate resistance, the changes affect the PR enzyme only at the level of the protein, whereas for multiple drug resistance, the RNA gene secondary structure also changes.
Keywords: Genomic signals, Pathogen variability, HIV, Influenza, Orthomyxoviridae, Drug resistance

1 Introduction

As shown in a series of previous papers [2-4], the conversion of nucleotide and amino acid sequences into digital signals offers the possibility to apply signal processing methods for the analysis of genomic data. The genomic signal conversion used in our work is a one-to-one mapping of symbolic genomic sequences into complex signals, as described in [2]. The idea is to conserve all the information in the initial symbolic sequence, while bringing in foreground some features significant for the subsequent processing and analysis. This direct method has proven its potential in revealing large scale features of DNA sequences, maintained at the scale of whole genomes or chromosomes, including both coding and non-coding regions. One of the most conspicuous results is that the unwrapped phase of DNA complex genomic signals varies almost linearly along all investigated chromosomes, for both prokaryotes and eukaryotes. The slope is specific for various taxa and chromosomes. This regularity of the genomic signals reveals a corresponding large scale regularity in the distribution of pairs of successive nucleotides, which is similar to Chargaff's first order rules for the frequencies of occurrence of the nucleotides [5].

We applied the same genomic signal approach for studying the variability of several pathogens, including the Human Immunodeficiency Virus, type 1 (HIV-1), subtype F, isolated from Romanian patients at the National Institute of Infectious Diseases "Prof. Dr. Matei Bals", Bucharest [3], and the avian influenza virus type A, based on genomic sequences downloaded from GenBank [1].We have used mainly the phase analysis of the complex genomic signals attached to the nucleotide sequences describing viral genes, as well as the analysis of the corresponding secondary RNA structure and of the phylogenetic neighbor-joining trees for some of these genes.

The focus of the study is primarily on the enzyme changes involved in generating pathogen resistance to multiple drug treatment. A novel methodology for describing sets of related genomic signals, based on a common reference and on individual differences has been developed. Variability signals with respect to average, median and maximum flat references, and digital derivatives of genomic signals are applied to this purpose. Applying this method, it has been found that the mutations in the genes of the analyzed viruses occur only in some specific, well defined locations, while the largest part of their genome remains unchanged. The mutations conferring drug resistance are a subset of all mutations occurring in the studied viruses.

On the other hand, for the case of HIV protease, it has been shown that the changes in response to the antiretroviral drug treatment occur not only at the level of the final enzyme product, preventing the action

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of the drug on the active protease catalytic site, but also at the level of protease gene RNA secondary structure. These type of changes have been found only for multiple drug resistant viruses.

2 Symbolic Sequence Conversion

For convenience we repeat here the mapping used in our work for the representation of the nucleotides [2]

$$a = 1 + j, c = -1 - j, g = -1 + j, t = 1 - j \tag{1}$$

Apart of the mapping of the four nucleotides (a,c,g,t), the complete genomic signal representation of nucleotide sequences also comprises the mapping of all the other IUPAC symbols for nucleotide classes: $s = \{c,g\}$ - strongly bonded, $w = \{a,t\}$ - weakly bonded, $r = \{a,g\}$ - purines, $y = \{c,t\}$ - pyrimidines, $m = \{a,c\}$ - amine, $k = \{g,t\}$ - ketone, $b = \{c,g,t\} = \neg a$, $d = \{a,g,t\} = \neg c$, $h = \{a,c,t\} = \neg g$, $v = \{a,c,g\} = \neg t$, and $n = \{a,c,g,t\}$ [2]. These symbols occur in the nucleotide sequences generated by genotyping because of the multiplicities determined either by the variability within the virus population or by noise. But this is not the case of the consensus sequences downloaded from GenBank [1], which are curated to contain only the (a,c,g,t) nucleotide symbols. The mapping in equation (1) has the advantage of conserving all the information in the initial symbolic sequence, as it uses a bijective mapping, while being as little biased as possible.

3 Representation by Reference and Variation

To study the variability of the genomic signals in a given set, for example, the signals for multiple resistant viruses, it is convenient to use a description comprising two types of components: (1) the reference - a certain signal considered to best describe the common variation of all components in the considered cluster; (2) the difference of each signal in the cluster with respect to the common reference. In such an approach, it is important to introduce in the common reference as much as possible of the variation shared by all the signals, and keep for the individual differences of each signal only the variations belonging actually to the that signal, without external variation.

The reference can be chosen as one of the following possibilities:

- average (mean) of the signals, or another linear combination of the signals;
- median - the signal in the central position, or the average of the pair of signals placed centrally;
- maximum flat signal - a modified median that keeps better local variations on the signals where they occur avoiding spurious transfers on other signals.

When the reference equals the average, the dispersion of the cluster of signals is minimum, i.e., the sum of the squares of the individual differences between each signal and the reference is minimized. But the average, as any other linear combination, has the important disadvantage that a localized variation of only one of the signals is transmitted to the reference, so that all the other signals will have an apparent variation of opposite sign in that point.

The median reference performs better, being a nonlinear function of the signals in the cluster, so that it decouples the common reference from the local variations of each of the individual signals. The median reference minimizes the sum of the absolute values of the differences between each signal and the reference. A variation localized on only one of the signals is no longer transmitted to the reference, so that it does not affect the variation with respect to the reference of the other signals. The exception occurs when the signal on which the localized variation occurs is just the median.

The maximum flat (MaxFlat) reference is equal to the median wherever the median has no variations which are not shared by other signals. Elsewhere, the MaxFlat reference assumes the minimal variation

that corresponds to its trend, if possible remaining constant. Consequently, the variation signals show better the changes that occur in each individual signal, with less "crosstalk". The digital derivatives of the variation signals show only the actual changes, caused by the variability in each of the signals and, for genomic signals, correspond directly to the SNPs.

4 HIV-1 Subtype F Variability

A phase analysis has been performed on a segment of about 1302 base pairs, approximately aligning with the standard sequence of HIV-1 (NC001802) in GenBank [1] over the interval 1799..2430 bp. This segment, which is currently used for the standard identification and assessment of HIV-1 strains, comprises the protease (PR) gene and almost two thirds of the reverse transcriptase (RT) gene. The PR and RT segments are contiguous and have been analyzed both together, as one entity, and independently, as two distinct encoding regions. The PR gene has the length 297 bp and is located in the first interval (1..297 bp) of the sequenced DNA segment, respectively along the 1799..2095 bp region of the NC001802 sequence. The RT encoding segment that has been analyzed has a length of 1005 bp and is located in the second interval (298..1302 bp) of the analyzed DNA segment, respectively along the 2096..3100 bp region of the NC001802 sequence. The entire RT gene has 1680 bp located in the interval 2096..3775 of the sequence.

Figures 1 and 2 show the cumulated and unwrapped phase of genomic signals for the protease (PR) genes from nine instances of HIV type 1, F clade [1, 6]. Three cases come from treatment naïve patients (S - sensitive), three from patients that developed resistance to one of the drugs (R), and three with multiple resistance to ther antiretroviral treatment (M). The cumulated phase is proportional to the unbalance in the number of nucleotides (statistics of first order) along the nucleic acid strand given by: $3(n_G - n_C) + (n_A - n_T)$, up to a $\pi/4$ factor, whereas the unwrapped phase is proportional to the difference between the number of direct and inverse nucleotide transitions (statistics of second order) along the nucleic acid strand $(n_+ - n_-)$, with a $\pi/2$ factor [2]. Figures 3 and 4 give the same informtion for the segment comprising 1005 bp of reverse transcriptase (RT) genes, out of the total of 1680 bp in this gene, for the same isolates in Figs. 1 and 2. As expected, the cumulated phase varies less than the unwrapped phase for these instances, as all mutations are of the SNP type and affect more the nucleotide pair distribution than the nucleotide distribution itself. Even for the unwrapped phase, the variation of the signal along the strand is quite similar for most of the sequences, but the local changes cumulate along the strands. Because of the mutations are local, the general shape of the phase signals are similar. It is also to be noticed that all the genomic material in these sequences is encoding and uses the same reading frame.

The vertical strips in these figures mark the positions of the mutations (SNPs) that induce resistance to protease inhibitors (Indinavir, Ritonavir, Saquinavir, Nelfinavir, and Amprenavir) [1]. The mutations that lead to multiple drug resistance are concentrated in several sites. In most of the remaining genome, the viruses have the same longitudinal structure. The sequences display mutations in several other locations. The effect of the mutations can easier be seen on the unwrapped phase, which is more sensitive to SNPs.

The successive mutations of the SNP type do not induce the divergence that could be expected, so that the signals do not actually diverge from one another. On the contrary, the signals tend to cluster, as the variations tend to compensate each other, so that the overall span of the signals does not increase directly with the number of mutations and the number of signals. This is another proof of the fact that, from the structural point of view, a genomic sequence satisfies more restrictions than a "plain text", which must just correspond to a certain semantics and to certain grammar rules, and resembles more to a “poem”, which additionally obeys rules of symmetry, giving its “rhythm” and “rhyme”. The recurrence of such patterned structures is reflected in simple mathematical rules satisfied by the corresponding genomic signals.

The representation can be improved by using the reference-difference description, choosing the maximum flat (MaxFlat) reference, as shown in Fig. 5 for the unwrapped phase in Fig. 4. In this case, the largest possible part of the common behavior of the signals is introduced in the reference signal, whereas each individual variation signal maintains only the changes occurring in that particular signal, or to the class it belongs to. The reference signal is no longer necessarily equal in each interval with one of the signals, even when the number of signals is odd. The digital derivatives of the difference signals, shown in Fig. 6 show only the actual changes caused by the variability in each of the signals. In the case of HIV, these changes correspond directly to the SNPs. For multiple resistant strains, the pulses correspond to the sites known from literature to confer resistance to various drugs.

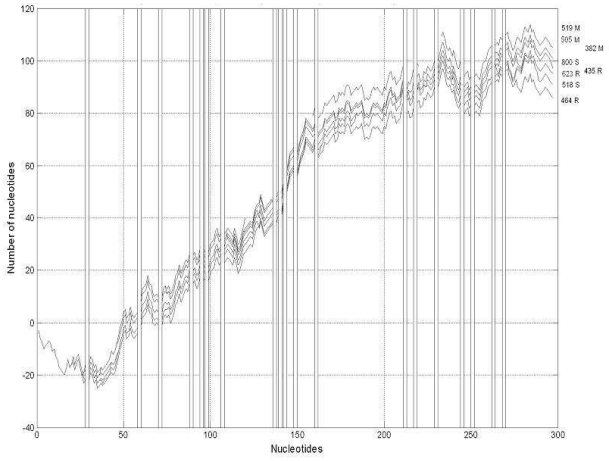

Figure 1: Cumulated phase expressed by $3(n_G - n_C) + (n_A - n_T)$ [2] for the protease (PR) gene of nine isolates of HIV-1, subtype F, showing sensitivity (S), resistance (R) and multiple resistance (M) to drugs.

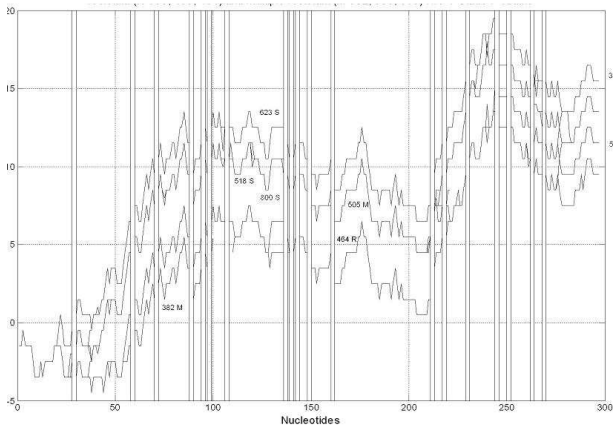

Figure 2: Unwrapped phase expressed by $n_+ - n_-$ [2] for the protease gene of the isolates of HIV-1 in Fig. 1.

HIV-1 makes many of its proteins in one long chain, and protease (PR) has the essential role of cutting this 'polyprotein' into the proper pieces, with the proper timing. Consequently, PR has been chosen as an important target for the current drug anti-HIV therapy. PR is a small enzyme, comprising two identical peptide chains, each of 99 amino acids long, which are encoded by the same gene of 297 nucleotides.

The two chains form a tunnel that holds the polyprotein, which is cut at an active site located in the center of the tunnel. Drugs bind to PR, blocking its action. Studying the estimated secondary structure

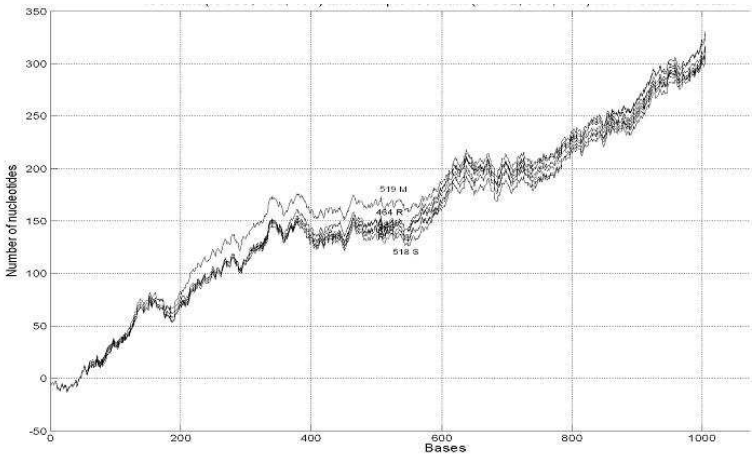

Figure 3: Cumulated phase of RT genomic signals for the isolates shown in Figs. 1 and 2.

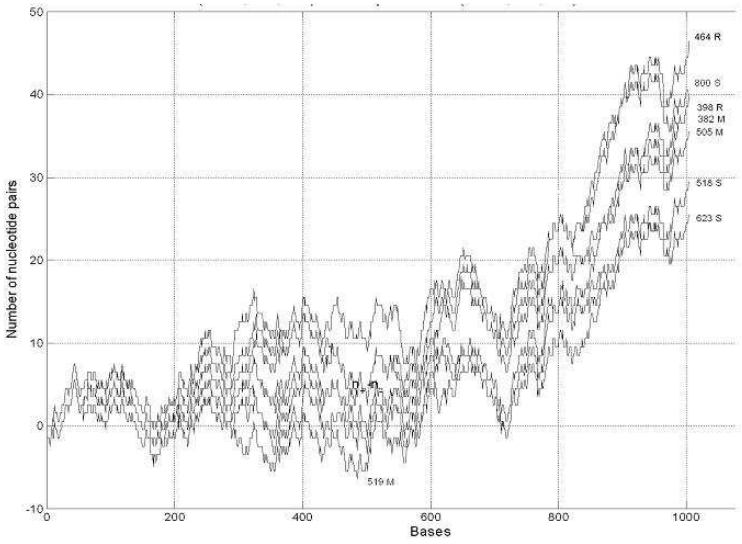

Figure 4: Unwrapped phase for the RT gene in the isolates shown in Figs. 1 and 2.

of the PR RNA for the nine virions previously analyzed, it can be shown [3] that the structures are quite similar for drug sensitive and drug simple resistant viruses. This result is consistent with the generally accepted model stating that the genomic changes of HIV, which induce resistance to drugs, operates at the level of the protein (the final protease enzime), preventing the blocking of its catalytic site. On the other hand, it is found the remarkable fact that, for drug multiple resistant strains, there is a significant change in the RNA secondary structure. Large loops and bulges are replaced with similar, but smaller, less vulnerable, closed-loop structures. These results indicate that there is a certain action of the drug at the level of the protease RNA, effect that becomes evident when mutations conferring multiple drug resistance occur.

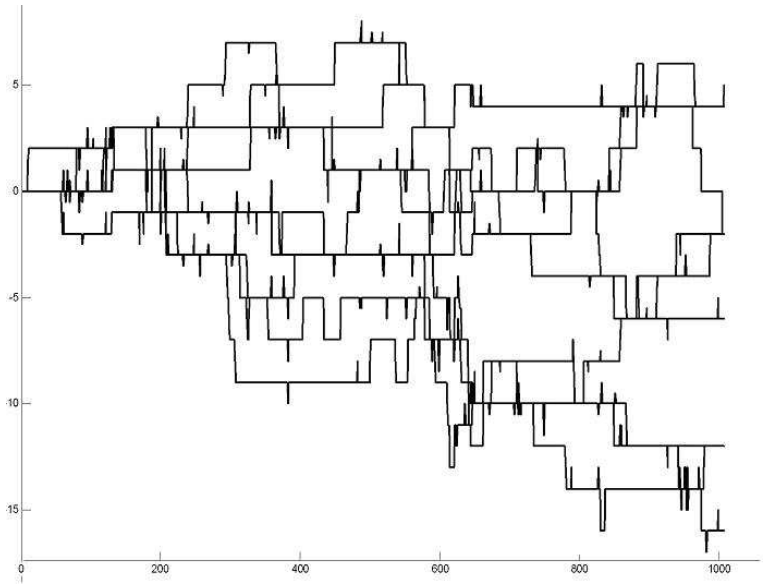

Figure 5: The unwrapped phase in Fig. 4 shown with respect to the *MaxFlat* reference.

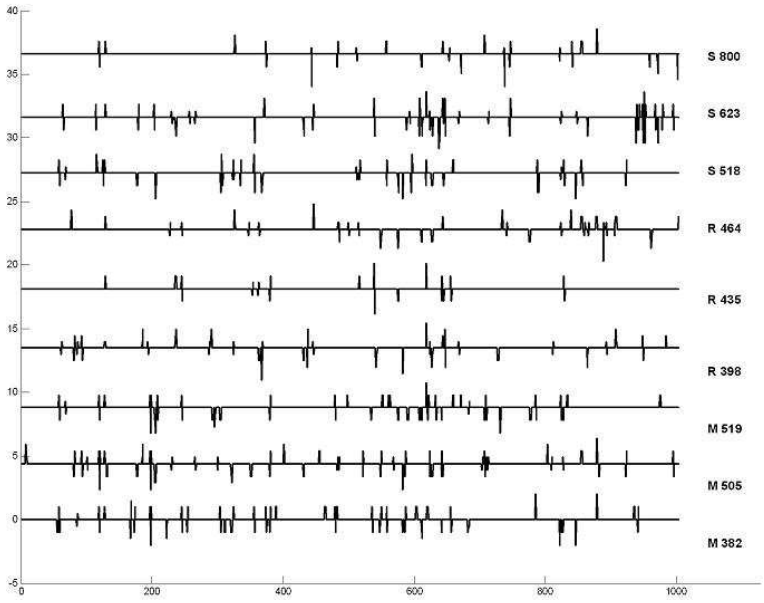

Figure 6: Digital derivatives of the variation signals in Fig. 5.

5 Variability of Hemagglutinin gene of influenza H5N1 virus

The influenza virus envelope embeds two specific antigenic glycoproteins that project out of the virion surface, the *Hemagglutinin* (HA) and the *Neuraminidase* (NA). Many different combinations of HA and NA proteins are possible, but only the H1N1 (Spanish endemic), H1N2 (Asian epidemic), and H3N2 (Hong Kong epidemic) subtypes have circulated worldwide among humans. HA protein selectively binds to the sialic acid of the host cell surface receptors, thus recognizing the cells that the virus can invade [4, 6]. Figure 7 gives the cumulated phase of the HA gene for H5N1 viruses isolated from two humans (AF046080, AF046097) and one chicken (AF046088), in Hong Kong, in 1997 [6, 7]. The genes for viruses isolated close in time are similar, even when crossing the inter-species barrier, whereas a large variation can be seen for genes isolated at larger time intervals. Only several SNPs are found in Fig. 8 which gives the difference cumulated phases with respect to the MaxFlat reference. The same result has been obtained for all the genes in the eight segments of the H5N1 virus [4, 6].

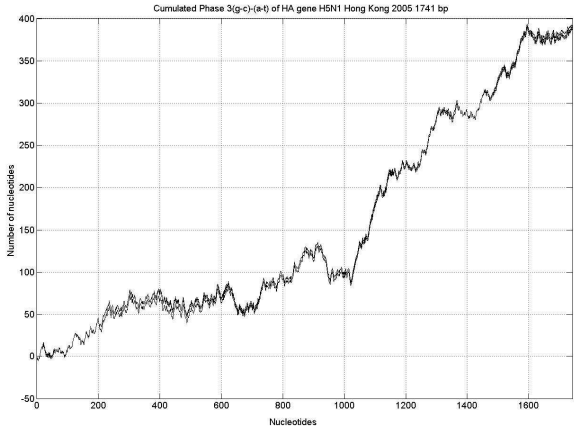

Figure 7: Cumulated phase of the HA gene, H5N1 virus (accessions AF046080, 88, 97 [1, 6]).

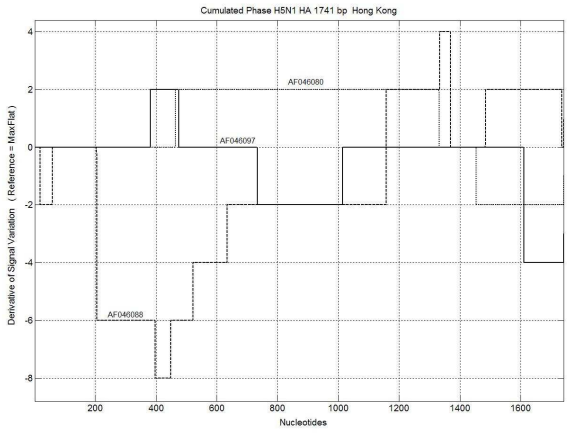

Figure 8: Differences of HA gene cumulated phases in Fig.7 with respect to the MaxFlat reference.

6 Further Work

Further work will be focused on:

- the dynamics of Influenza Type A viruses that have crossed till now the species barrier from birds to humans, and which hold the potential to become highly contagious and highly lethal in humans, including the H5N1 subtype,
- extending the study from the nucleotide to the amino acid level, which could be more significant from the phenotypic point of view,
- using genomic signals for helping clustering viruses in classes.

Acknowledgments

The sequences of HIV presented in this paper have been genotyped by Dr. Dan Otelea from the National Institute of Infectious Diseases “Prof. Dr. Matei Bals”, Bucharest, Romania. Results referring to the study of HIV variability have been previously jointly published [3].

References

[1] National Center for Biotechnology Information, National Institutes of Health, National Library of Medicine, National Center for Biotechnology Information, GenBank, http://www.ncbi.nlm.nih.gov/genoms

[2] P. D. Cristea, "Representation and Analysis of DNA sequences", in Genomic Signal Processing and Statistics, Editors E.G. Dougherty, I. Shmulevici, Jie Chen, Z. J. Wang, Book Series on Signal Processing and Communications, Hidawi, 2005, pp.15-65.

[3] P. D. Cristea, D. Otelea, Rodica Tuduce, "Study of HIV Variability Based on Genomic Signal Analysis of Protease and Reverse Transcriptase Genes", EMBC’05, Sept. 2005, Shanghai, China.

[4] P. D. Cristea, "Genomic Signal Analysis of Pathogen Variability", SPIE, BO24, paper 5699-52, San Jose, Jan, 2005, 12 pg.

[5] E. Chargaff, "Structure and function of nucleic acids as cell constituents", Fed. Proc., 10, pp. 654-659, 1951.

[6] D.L. Suarez,.et.al., Comparisons of highly virulent H5N1 influenza A viruses isolated from humans and chickens from Hong Kong, J. Virology, vol. 72 (8), pp. 6678-6688, 1998. (AF046080-99).

[7] E. Ghedin, N. Sengamalay, M. Shumway et. al., "Large-scale sequencing of human influenza reveals the dynamic nature of viral genome evolution", Nature, vol. 437, Oct. 2005, pp.1162-1166.

[8] M.S. Hirsch et al., "Antiretroviral Drug Resistance Testing in Adult HIV-1 Infection", in Proc. Recommendations of an International AIDS Society - USA Panel, JAMA, vol. 283, no. 18, May 10, 2000, pp.2417-2426.

Paul Dan Cristea
University POLITEHNICA of Bucharest
Biomedical Engineering Center
Address: Spl. Independentei 313, sect. 6
060042 Bucharest, Romania
E-mail: pcristea@dsp.pub.ro

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Descriptive Timed Membrane Petri Nets for Modelling of Parallel Computing

Emilian Guţuleac

Abstract: In order to capture the compartmentation and behaviour of membrane systems for modelling of parallel computing, we introduce the descriptive dynamic rewriting Descriptive Membrane Timed Petri Nets (DM-nets) that can at in run-time modify their own structure by rewriting some of their descriptive expression components. Furthermore, this descriptive approach facilitates the understanding of complex models and their component-based construction as well as the application of modern computer engineering concepts.
Keywords: Descriptive Petri nets, membrane systems, modelling, parallel computing.

1 Introduction

Recent technological achievements require advances beyond the existing computational models in order to be used effectively. Pragmatic aspects of current and future computer systems will be modelled so that realistic estimates of efficiency can be given for algorithms in these new settings.

Petri nets (PN) are very popular formalism for the analysis and representation of parallel and distributed computing in concurrent systems that has draw much attention to modelling and verification of this type of systems [1].

P systems, also referred to as membrane systems, are a class of parallel and distributed computing models [6]. The interest of relating P systems with the PN model of computation lead to several important results on simulation and decidability issues. Some efforts have been made to simulate P systems with Petri nets [2, 5, 7] to verifying the many useful behavioral properties such as reachability, boundedness, liveness, terminating, etc.

In this paper we propose a new approach to express the components of continuous-time P systems [6] throughout components of escriptive Petri Nets (PN) using descriptive expressions (DE) [3] for modelling of parallel computing. The DE are used for analytical representation and compositional construction of PN models. To model specific rules of P-systems within the framework of the descriptive Rewriting Timed PN (RTN) [4] we introduce a new extensions Ű the descriptive Membrane RTN, called DM-nets, that can modify dynamically their own structures by rewriting rules some of their components.

2 Labeled Extended Petri Nets

In this section, we define a variant of PN called labeled extended PN. Let L be a set of labels $L = L_P \uplus L_T$. Each place p_i labeled $l(p_i) \in P$ a local state and transition t_j has action labeled as $l(t_j) \in L_T$.

A labeled extended PN is structure as a $\Gamma =< P, T, Pre, Post, Test, Inh, G, Pri, K_p, l >$, where: P is the finite set of places and T is a finite set of transitions that $P \cap T = \emptyset$. In the graphical representation, the place is drawn as a circle and the transition is drawn as a black bar; The Pre, $Test$ and $Inh : P \times T \times \mathcal{N}^{|\mathcal{P}|} \to \mathcal{N}_+$ respectively is a forward flow, test and inhibition functions and is a backward flow function in the multi-sets of P, where defined the set of arcs A and describes the marking-dependent cardinality of arcs connecting transitions and places. The set A is partitioned into tree subsets: A_d, A_h, and A_t. The subset A_d contains the directed arcs which can be seen as A_d: $((P \times T) \cup (T \times P)) \times \mathcal{N}^{|\mathcal{P}|} \to \mathcal{N}_+$ and are drawn as single arrows. The inhibitory arcs $A_h : (P \times T) \times \mathcal{N}^{|\mathcal{P}|} \to \mathcal{N}_+$are drawn with a small circle at the end. The test arcs $A_t : (P \times T) \times \mathcal{N}^{|\mathcal{P}|} \to \mathcal{N}_+$are directed from a place to a transition, and are drawn as

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dotted single arrows. It does not consume the content of the source place. The arc of net is drawn if the cardinality is not identically zero and this is labeled next to the arc and by a default value being 1; $G : E \times \mathcal{N}^{|\mathcal{P}|} \to \{true, false\}$ is the guard function transitions. For $t \in T$ a guard function $g(t,M)$ that will be evaluated in each marking, and if it evaluates to *true*, the transition t may be enabled, otherwise t is disabled (the default value is *true*); $Pri : T \to \mathcal{N}_+$ defines the priority functions for the firing of each transition that maps transitions onto natural numbers representing their priority level. The enabling of a transition with higher priority disables all the lower priority transitions; $K_p : P \to \mathcal{N}_+$ is the capacity of places, and by default being infinite value; The $l : T \cup P \to L$, is a labeling function that assigns a label to a transition and places. In this way that maps transition name into action names that $l(t_j) = l(t_k) = \alpha$ but $t_j \neq t_k$ and $l(p_i) = l(p_n) = \beta$ but $p_i \neq p_n$.

A marked labeled extended PN net is a pair $N =< \Gamma, M_0 >$, where Γ is a labeled PN structure and M_0 is the initial marking of the net. $M : P \to \mathcal{N}_+$ is the current marking of net which is described by a symbolic vector-column $M = (m_i p_i), m_i \geq 0, \forall p_i \in P$, where the $(m_i p_i)$ is the number m_i of tokens in place p_i. The M is the state of net that assigns to each place tokens, represented by black dots.

The details concerning on enabling and firing rules, and evolution for of $N =< \Gamma, M_0 >$ can be found in [3] as they require a great deal of space.

3 Descriptive expressions of Petri nets

Due to the space restrictions we will only give a brief overview to this topic and refer the reader to [3, 4] and the references therein. In following for abuse of notation, labels and name of transitions/places are the same. We use the concept of a basic descriptive element (*bDE*) for a basic PN (*bPN*) introduced in [2] as following: $bDE = |_{t_j}^{\alpha_j} m_i^0 p_i [W_i^+, W_i^-] |_{t_k}^{\alpha_k}$. The translation of this *bPN* is shown in figure 1a, where respectively is input transition (action type α_j) and $t_k = p_i^\bullet$ is the output transition (action type α_k) of place $p_i \in P$ with initial marking m_i^0, and the flow type relation functions $W_i^+ = Pre(t_j, p_i)$ and $W_i^- = Post(t_j, p_i)$, respectively which return the multiplicity of input and output arcs of the place $p_i \in P$. The derivative elements of *bDE* are for $p_i^\bullet = \emptyset, W_i^- = 0$ is $|_{t_j}^{\alpha_j} m_i^0 [W_i]$ with final place p_i of t_j and ${}^\bullet p_i = \emptyset, W_i^+ = 0$ is $m_i^0 p_i [W_i] |_{t_k}^{\alpha_k}$ with entry place p_i of t_k. If the initial marking m_i^0 of place is a zero tokens we can omit m_i^0 in *bDE*. By default, if the type of action α is not mentioned this to match the name of a transition t. From a *bDE* we can build more complex DE of PN components by using composition operations. Also by default,if $W_i^+ = W_i^- = 1$, we present *bDE* and it derivatives as following:$|_{t_j}^{\alpha_j} m_i^0 p_i |_{t_k}^{\alpha_k}$, $|_{t_j}^{\alpha_j} m^0 p_i$ or $m_i^0 p_i |_{t_k}^{\alpha_k}$.

A descriptive expression (*DE*) of a labeled PN is either *bDE* or a composition of *DE* a *N*: $DE ::= bDE | DE * DE | \circ DE$, where $*$ represents any binary composition operation and $\circ$ any unary operation.

Descriptive Compositional Operations. In the following by default the labels of *N* are encoded in the name of the transitions and places. The composition operations are reflected at the level of the *DE* components of *N* models by fusion of places, fusion of transitions with same type and same name (label) or sharing of as subnets.

Place-Sequential Operation. This binary operation, denoted by the " | " *sequential operator*, determines the logic of a interaction between two local states p_i (pre-condition) and p_k (post-condition) by t_j action that are in precedence and succeeding (causality-consequence) relation relative of this action. Sequential operator is the *basic mechanism* to build *DE* of *N* models. This operation is an *associative*, *reflexive* and *transitive* property, but is *not commutative* operation. The means the fact $DE1 = m_i^0 p_i [W_i] |_{t_j}^{\alpha_j} m_k^0 p_k [W_k] \neq m_k^0 p_k [W_k] |_{t_j}^{\alpha_j} m_i^0 p_i [W_i]$ that the specified conditions (local state) associated with place-symbol p_i are fulfilled always happens before then the occurrence of the conditions associated with place-symbol p_k by means of the action t_j. Also, the PN modelling of the *iteration* operation is obtained by the fusion of head (entry) place with the tail (final) place that are the same name (*closing* operation) in *DE* which describes this net. The self-loop of $N2$ net described by an:

$DE2 = m_i^0 p_i[W_i]|_{t_j}^{\alpha_j} p_i[W_i] = m_i^0 \tilde{p}_i[W_i]|_{t_j}^{\alpha_j}$, it is the test operator "$\tilde{p}$", i.e. represent the *test* arc. The translation of $DE2$ in $N2$ is shows in figure 2b.

Inhibition Operation. This unary operation is represented by inhibitory operator "- " (place-symbol with overbar) and it $DE3 = m_i^0 \bar{p}_i[W_i]|_{t_j}^{\alpha_j}$ describe the inhibitor arc with a weight $W_i = Inh(p_i, t_j)$.

Synchronization Operation. This binary operation is represented by the " $\bullet$" or " $\wedge$"*join* operator describe the rendez-vous synchronization (by transition t_{t_j}) of a two or more conditions represented respectively by symbol-place $p_i \in^\bullet t_j, i = \overline{1,n}$, i.e. it indicate that all preceding conditions of occurrence actions must have been completed. This operation is a commutative, associative and reflexive.

Split Operation . This binary operation represented by the " $\diamondsuit$" *split* operator and it describe the causal relations between activity $t_j$and its post-conditions: after completion of the preceding action of t_j concomitantly several other post-condition can take occurs in parallel ("message sending"). Property of split operation is a commutative, associative and reflexive.

Competing Parallelism Operation. This compositional binary operation is represented by the " $\vee$" competing parallelism operator, and it can be applied over two N_A with $DE_A = A$ and N_B with $DE_B = B$ or internally into resulting N_R with $DE_R = R$, between the places of a single N_R which the symbol-places with the same name are fused, respectively. We can represent the resulting $DE_R = A \vee B$ as a set of ordered pairs of places with the same name to be fused, with the first element belonging to A the second to B. The fused places will inherit the arcs of the place in A and B . Also, this compositional binary operation is a *commutative*, *associative* and *reflexive* property.

Precedence Relations between the Operations. We introduce the following precedence relation between the compositional operations in the DE: a) the evaluation of operations in DE are applied left-to-right; b) an unary operation binds stronger than a binary one; c) the "$\bullet$ "operation is superior to"|" and " $\diamondsuit$", in turn, its are superior the "$\vee$ " operation. Further details on definitions, enabling and firing rules, and evolution for of N can be found in [3] as they require a great deal of space.

4 Dynamic Rewriting Petri Nets

In this section we introduce the model of *descriptive dynamic net rewriting* PN system. Let $X\rho Y$ is a binary relation. The *domain* of is the $Dom(\rho) = \rho Y$and the *codomain* of ρ is the $Cod(\rho) = X\rho$. Let $A =< Pre, Post, Test, Inh >$ is a set of arcs belong to netΓ .

A descriptive dynamic rewriting PN system is a structure $RN =< \Gamma, R, \phi, G_{tr}, G_r, M >$,
where: $=< P, T, Pre, Post, Test, Inh, G, Pri, K_p, l >$; $R = r_1, ..., r_k$ is a finite set of rewriting rules about the runtime structural modification of net that $P \cap T \cap R = \emptyset$. In the graphical representation, the rewriting rule is drawn as a two embedded empty rectangle. We let $E = T \cup R$ denote the set of events of the net; $\phi : E \to T, R$ is a function indicate for every rewriting rule the type of event can occur; $G_{tr} : R \times \mathcal{N}^{|\mathcal{P}|} \to \{true, false\}$ and $G_r : R \times \mathcal{N}^{|\mathcal{P}|} \to \{true, false\}$ is the *transition rule guard function* associated with $r \in R$ and the rewriting rule guard function defined for each rule of $r \in R$, respectively. For $\forall r \in R$, the $g_{tr} \in G_{tr}$ and $g_r \in G_r$will be evaluated in each marking and if its are evaluates to *true*, the rewriting rule r may be *enabled*, otherwise it is disabled. Default value of $g_{tr} \in G_{tr}$ is *true* and for $g_r \in G_r$ is *false*. Let $RN =< R\Gamma, M >$ and $R\Gamma =< \Gamma, R, \phi, G_{tr}, G_r >$ described with the descriptive expression $DE_{R\Gamma}$ and DE_{RN}, respectively. A dynamic rewriting structure modifying rule $r \in R$ of RN is a map $r : DE_L \rhd DE_W$, where whose *codomain* of the rewriting operator $\rhd$ is a fixed descriptive expression DE_L of a subnet RN_L of current net RN, where $RN_L \subseteq RN$,with $P_L \subseteq P$, $E_L \subseteq E$and set of arcs $A_L \subseteq A$ and whose *domain* of the $\rhd$ is a descriptive expression DE_W of a new RN_W subnet with $P_W \subseteq P$, $E_W \subseteq E$ and set of arcs A_W. The $\rhd$ rewriting operator represent binary operation which produce a *structure change* in the DE_{RN} and the net RN by replacing (rewriting) of the fixed current DE_L of subnet RN_L (DE_L and RN_L are dissolved) by the new DE_W of subnet RN_W now belong to the new modified resulting $DE_{RN'}$ of net $RN^{'} = (RN \backslash RN_L) \cup RN_W$ with $P^{'} = (P \backslash P_L) \cup P_W$ and $E^{'} = (E \backslash E_L) \cup E_W$, where $A^{'} = (P \backslash P_L) \cup A_W$ the meaning of $\backslash$ (and $\cup$) is

operation to removing (adding) RN_L from ($RN_W$to) net RN. In this new net $RN^{'}$, obtained by execution (fires) of enabled rewriting rule $r \in R$, the places and events with the same attributes which belong $RN^{'}$ are fused, respectively. By default the rewriting rules $r : DE_L \rhd \emptyset$ and$r : \emptyset \rhd DE_W$ describe the rewriting rule which fooling holds $RN^{'} = (RN \backslash RN_L)$ and $RN^{'} = (RN \cup RN_W)$, respectively. A state of a net RN is a pair $(R\Gamma, M)$, where $R\Gamma$ is the configuration of net together with a current marking M. Also, the pair $(R\Gamma_0, M_0)$ with $P_0 \subseteq P$, $E_0 \subseteq E$ and marking M_0 is called the initial state of the net.

Enabling and Firing of Events. The enabling of events depends on the marking of all places. We say that a transition t_j of event e_j is enabled in current marking M if the following enabling condition $ec(t_j, M)$ is verified:

$ec(t_j, M) = (\wedge_{\forall p_i \in {}^\bullet t_j}(m_i \geq Pre(p_i, t_j)) \wedge (\wedge_{\forall p_k \in {}^\circ t_j}(m_k < Inh(p_i, t_j))) \wedge (\wedge_{\forall p_l \in {}^* t_j}(m_l \geq Test(p_l, t_j))) \wedge (\wedge_{\forall p_n \in t_j^\bullet}((K_{p_n} - m_i) \geq Post(p_n, t_j)))) \wedge g(t_j, M))$.

Similarly, the rewriting rule $r_j \in R$ is enabled in current marking M if the following enabling condition $ec_{tr}(r_j, M)$is verified:

$ec_{tr}(r_j, M) = (\wedge_{\forall p_i \in {}^\bullet r_j}(m_i \geq Pre(p_i, r_j)) \wedge (\wedge_{\forall p_k \in {}^\circ r_j}(m_k < Inh(p_i, r_j))) \wedge (\wedge_{\forall p_l \in {}^* r_j}(m_l \geq Test(p_l, r_j))) \wedge (\wedge_{\forall p_n \in r_j^\bullet}((K_{p_n} - m_i) \geq Post(p_n, r_j)))) \wedge g(r_j, M))$.

Let the $T(M)$ and $R(M)$ is respectively the set of enabled transitions and rewriting rule in current marking M. Let the $E(M) = T(M) \uplus R(M)$, is the set of enabled events in a current marking M. The event $e_j \in E(M)$ fire if no other event $e_k \in E(M)$ with higher priority has enabled. Hence, for e_j event $if((\phi_j = t_j) \vee (\phi_j = r_j) \wedge (g_{tr}(r_j, M) = false))$ *then* (the firing of transition $t_j \in T(M)$ or rewriting rule $r_j \in R(M)$ change only the current marking:$(R\Gamma, M) \stackrel{e_j}{\rightarrow} (R\Gamma, M^{'}) \Leftrightarrow (R\Gamma = R\Gamma^{'}$ and $M[e_j > M^{'}))$. Also, for e_j event $if((\phi_j = r_j) \wedge (g_r(r_j, M) = true)$ *then* (the event e_j occur to firing of rewriting rule r_j and it occurrence change configuration and marking of current net:$(R\Gamma, M) \stackrel{r_j}{\rightarrow} (R\Gamma^{'}, M^{'})$, $M[r_j > M^{'}$).

The accessible state graph of a net$RN =< \Gamma, M >$ is the labeled directed graph whose nodes are the states and whose arcs which is labeled with events of RN are of two kinds: a) firing of a enabled event $e_j \in E(M)$: arcs from state $(R\Gamma, M)$ to state$(R\Gamma, M^{'})$ labeled with evente_j then this event can fire in the net configuration $R\Gamma$ at marking M and leads to new marking $M^{'}$: $(R\Gamma, M) \stackrel{e_j}{\rightarrow} (R\Gamma^{'}, M^{'}) \Leftrightarrow (R\Gamma = R\Gamma^{'}$ and $M[e_j > M^{'}$ in $R\Gamma)$; b) change configuration: arcs from state $(R\Gamma, M)$ to state($R\Gamma^{'}, M^{'}$) labeled with rewriting rule r_j :$(R\Gamma_L, M_L) \rhd (R\Gamma_W, M_W)$ which represent the change configuration of current RN net: $(R\Gamma, M) \stackrel{e_j}{\rightarrow} (R\Gamma^{'}, M^{'})$ and $M[r_j > M^{'}$.

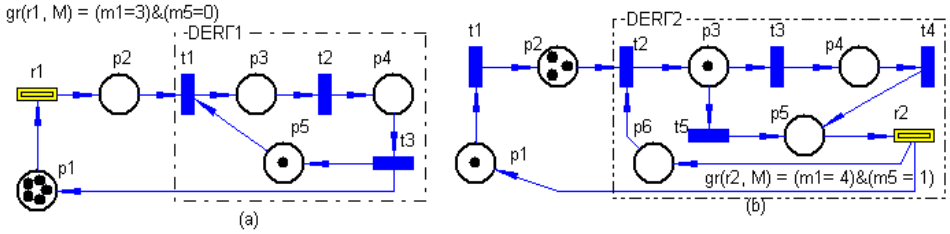

Figure 1: Translation of (a) $DE_{R\Gamma 1}$in $RN1$ and (b) $DE_{R\Gamma 2}$ in $RN2$

Let we consider the $RN1$ given by the following descriptive expression:$DE_{R\Gamma 1} = p_1|_{r_1} p_2 \vee DE^{'}_{R\Gamma 1}$, $DE^{'}_{R\Gamma 1} = (p_2 \cdot p_5)|_{t_1} p_3|_{t_2} p_4|_{t_3}(p_1 \diamondsuit p_5)$, $M_0 = (5p_1, 1p_5)$, $g_r(r_1, M) = (m_1 = 3)\&(m_5 = 0)$ and $r_1 : DE_{R\Gamma 1} \rhd DE_{R\Gamma 2}$. Also, for r_j is required to identify if RN_L belong the $R\Gamma$. Upon firing, the enabled events or rewriting rule modify the current marking and/or and modify the structure and current marking of net $RN1$ in $RN2$ given by: $DE_{R\Gamma 2} = p_1|_{t_1} p_2 \vee DE^{'}_{R\Gamma 2}$, $DE^{'}_{R\Gamma 2} = (p_2 \cdot p_6)|_{t_2} p_3(|_{t_3} p_4|_{t_4} p_5 \vee |_{t_5} p_5|_{r_2}(p_1 \diamondsuit p_6))$, $M = (1p_1, 3p_2, 1p_3)$, $g_r(r_2, M) = (m_1 = 4)\&(m_5 = 1)$, $r_2 = r_1^{-1} : DE_{R\Gamma 2} \rhd DE_{R\Gamma 1}$.

Figure 1 show the translation of $DE_{R\Gamma 1}$ in $RN1$ and $DE_{R\Gamma 2}$ in $RN2$, respectively.

5 Dynamic Rewriting Timed Petri Nets

Systems are described in timed PN (TPN) as interactions of components that can performed a set of activities associated with events. An event $e = (\alpha, \theta)$, where $\alpha \in E$ is the type of the activity (action name), and θ is the firing delay.

A descriptive dynamic rewriting TPN as a $RTN =< RN, \theta >$, where: $RN =< \Gamma, R, \phi, G_{tr}, G_r, M >$, $\Gamma =< P, T, Pre, Post, Test, Inh, G, Pri, Kp, l >$ (see Definition 2 and 3) with set of events E which can be partitioned into a set E_0 of *immediate* events and a set E_τ of *timed* events $E = E_0 \uplus E_\tau$. The immediate event is drawn as a thin bar and timed event is drawn as a black rectangle for transition or a two embedded empty rectangle for rewriting rules, and $Pri(E_0) > Pri(E_\tau)$; $\theta : E \times \mathbb{N}^{|\mathcal{P}|} \to \mathcal{R}_+$ is the weight function that maps events onto real numbers $\mathcal{R}_+$ (delays or weight speeds). Its can be marking dependent. The delays $\theta(e_k, M) = d_k(M)$defining the events firing parameters governing its duration for each timed events of E_τ. If several timed events are enabled concurrently $e_j \in E(M)$ for $e_j \in {}^\bullet p_i = \forall e_j \in E : Pre(p_i, e_j) > 0$, either in competition or independently, we assume that a race race competition condition exists between them. The evolution of the model will determine whether the other timed events have been aborted or simply interrupted by the resulting state change. The $\theta(e_j, M) = w_j(M)$ is weight speeds of immediate events $e_{j \in E_0}$. If several enabled immediate events are scheduled to fire at the same time in *vanishing* marking M with the weight speeds, and the probability to enabled immediate event e_j can *fire* is: $q_i(M) = w(e_j, M) / \sum_{e_l \in (E(M) \& {}^\bullet p_i)} w(e_j, M)$,where $E(M)$ is the set of enabled events in M. An immediate events $e_j \in T_0$ has a zero firing time.

6 P Systems and Descriptive Timed Membrane Petri Nets

Here we give a brief review of P systems and its encoding with DM-nets. The main components of P systems are membrane structures consisting of membranes hierarchically embedded in the outermost skin membrane. A full guide for P systems can be referred to [3]. In general, a basic evolution-communication P system with *active membranes* (of degree $n \geq 0$) is $\Pi = (O, H, \mu, \Omega, (\rho, \pi))$, where: O is the alphabets of objects; H is a finite set of labels for membranes;μ is a membrane structure consisting of n membranes labeled with elements h in H;Ω is the configuration, that is a mapping from membranes of Π(nodes in μ) to multisets of objects $\omega_k \in \Omega, k = 1, , |\Omega|$, from O;ρ and π is respectively the set off developmental rules ρ_h and $\pi_h$its priorities , $h = 0, 1, , n-1$. Thus the can be of two forms of rules: a) the *object rules* (OR), i.e., evolving and communication rules concerning the objects; b) the membranes rules (MR), i.e., the rules about the structural modification of membranes.

Here we define DM-Nets for encoding of P systems mentioned above into descriptive dynamic rewriting TPN as a RTN. The basis for DM-Nets is a membrane RTN that is DE net structure comprise: places; transitions; weighed directed arcs from places to transitions and vice-versa; a capacity for each place; weighed inhibitory and test arcs; priority and guard function of transitions.

The $DM - nets$ of degree $n \geq 0$ is a construct $DM = \vee_{h=0}^{n-1} [_h DE_h]_h$, where DE_h is the descriptive expression of RTN_h that represent the configuration of membrane $[_h \,]_h$ in a P system Π.

Consider the P system Π.The encoding of Π into RTN_Π is decomposed into two separate steps. First, for every membrane $[_h \,]_h$ we associate: to each object $\omega_i \in \Omega$ one place $p_{h,i} = [_h m_i^0 \, p_i]_h$ labeled as ω_i with the initial marking m_i^0, and to each rule $\rho_{h,j} \in \rho$ one event $e_{h,j} = [_h e_j]_h$ labeled as $\rho_{h,j}$ that acts on the this membrane. Second, for every membrane $[_h \,]_h$ we define the DE_h of RTN_h that it correspond to the initial configuration of the P system Π as $[_h DE_h]_h$.

Let u, v , and $u_\prime, v_\prime$, is a multiset of objects. The *evolving* object rule $\rho_{h',j} : [_h [_{h'} u \to v]_{h'}]_h$ with multiset of objects u, v , which will be kept in membrane $[_h]_h$ is encoded as $[_h [_{h'} \, p_u |_{t_j} p_v]_{h'}]_h$. The antiport rule $\rho_{h',j} : [_h u [_{h'} v]_{h'}]_h \to [_h v' [_{h'} u']_{h'}]_h$, that realize a synchronized wich object c the exchange of objects, is encoded as $[_h [_{h'} (p_u \cdot p_v \cdot \tilde{p}_c) |_{t_j} (p_{u'} \diamondsuit p_{v'})]_{h'}]_h$. Also, the symport rule $\rho_{h',k} : [_h u [_{h'}]_{h'}]_h \to [_h [_{h'} u']_{h'}]_h$ that

move objects from inside to outside a membrane, or vice-versa is encoded as $[_h[_{h'}(p_u \cdot \tilde{p}_c)|_{t_k} p_{u'}]_{h'}]_h$.

Because a configuration mean both a membrane structure and the associated multisets, we need rules for processing membranes and multisets of objects as:

$MR = Change, Dissolve, Create, Divide, Merge, Separate, Move.$

The above membrane rewriting rules (realized by the rewriting events in DE) are defined as follows:

*Change*rewriting rule $[_h[_{h'}(DE_{h'}, M_{h'})]_{h'}]_h \rhd [_h[_{h'}(DE^{'}_{h'}, M^{'}_{h'})]_{h'}]_h$ that in runtime the current structure and the multisets of objects to membrane h, encoded by descriptive expression $DE_{h,}$ and marking $M_{h,}$ is changed in a new structure $DE^{'}_{h,}$ with new marking $M^{'}_{h,}$;

Dissolve rewriting rule $[_h(DE_h, M_h)[_{h'}(DE_{h'}, M_{h'})]_{h'}]_h \rhd [_h(DE_h, M^{'}_h)]_h$ that the objects and sub-membranes of membrane $h^{'}$ now belong to its parent membrane h , the skin membrane cannot be dissolved;

Create rewriting rule $[_h(DE_h, M_h)]_h \rhd [_h(DE^{'}_h, M^{'}_h)[_{h'}(DE^{''}_{h'}, M^{''}_{h'})]_{h'}]_h$ with $M_h = M^{'}_h + M^{''}_{h'}$ that the new membrane $h^{'}$ is created and $M^{''}_{h'}$ are added into membrane $h^{'}$, the rest remain in the parent membrane h; Divide rewriting rule $[_h(DE_h, M_h)]_h \rhd [_h[_{h'}(DE_h, M_h)]_{h'}[_{h''}(DE_h, M_h)]_{h''}]_h$that the objects and sub-membranes are reproduced and added into membrane $h^{'}$ and membrane $h^{''}$, respectively;

Merge rewriting rule that the objects of membrane $h^{'}$ and $h^{''}$ are added to a new membrane h is: $[_h[_{h'}(DE^{'}_{h'}, M_{h'})]_{h'}[_{h''}(DE^{''}_{h''}, M^{''}_{h''})]_{h''}]_h \rhd [_h(DE^{'}_{h'} \vee DE^{''}_{h''}, M_{h'} + M^{''}_{h''})]_h$;

Separate rewriting rule is the counterpart of *Merge* is done by a rewriting rule of the form $\rhd [_h(DE^{'}_{h'} \vee DE^{''}_{h''}, M_{h'} + M^{''}_{h''})]_h \rhd [_h[_{h'}(DE^{'}_{h'}, M_{h'})]_{h'}[_{h''}(DE^{''}_{h''}, M^{''}_{h''})]_{h''}]_h$ with the meaning that the content of membrane h is split into two membranes, with labels $h^{'}$ and $h^{''}$.

*Move*rewriting rule where a membrane $h^{''}$ can be moved out or moved into a membrane $h^{'}$ as a whole is: $[_h[_{h'}(DE_{h'}, M_{h'})[_{h''}(DE^{''}_{h''}, M^{''}_{h''})]_{h''}]_{h'}]_h \rhd [_h[_{h'}(DE_{h'}, M_{h'})]_{h'}[_{h''}(DE^{''}_{h''}, M^{''}_{h''})]_{h''}]_h$ or

$[_h[_{h'}(DE_{h'}, M_{h'})]_{h'}[_{h''}(DE^{''}_{h''}, M^{''}_{h''})]_{h''}]_h \rhd [_h[_{h'}(DE_{h'}, M_{h'})[_{h''}(DE^{''}_{h''}, M^{''}_{h''})]_{h''}]_{h'}]_h$.

Thus, using the $DM-Nets$ facilitates a compact and flexible specification to visual simulate of P systems with dynamic rewriting TPN nets that permit the verification of the its many useful behavioral properties such as reachability, boundedness, liveness, terminating, etc., and the performance evaluation of parallel computing models.

7 Summary and Conclusions

In this paper we have proposed an approach to the performance modeling of the behaviour of P-systems through a class of Petri nets, called Descriptive Membrane Timed PN (DM-nets). Based upon the introduction of a set of descriptive composition operation and rewriting rules attached with transitions for the creation of dynamic rewriting TPN, the membrane structure can be successfully encoded as a membrane descriptive rewriting timed Petri nets models which permit the description the behavioral state based process run-time structure change of P systems. We are currently developing a software visual simulator with a friendly interface for verifying and performance evaluation of descriptive rewriting TPN models and DM-nets.

References

[1] M. Ajmone-Marsan, G. Balbo, G. Conte, S. Donatelli, and G. Francheschinis, “Modeling with Generalized Stochastic Petri Nets,” *ser. In Parallel Computing* ,New York: Wiley, 1995.

[2] S. Dal Zilio, E. Formenti, “On the Dynamics of PB System: a Petri Net View,” *In Proceedings WMC 2003, Lecture Notes in Computer Science 2933* , Springer-Verlag, pp. 153-167, 2004.

[3] E. Gutuleac, "Descriptive Compositional Construction of GSPN Models for Performance Evaluation of Computer Systems," *In Proceedings of the 8-th International Symposium on Automatic Control and Computer Science, SACCS2004, 22-23 October*,Iasi, Romania, CD, 2004.

[4] E. Gutuleac, "Descriptive Dynamic Rewriting GSPN-based Performance Modeling of Computer Systems," *Proceedings of the 15th International Conference on Control Systems and Computer Science, CSCS15, 25-27 May 2005*,Bucuresti, Romania, pp. 656-661, 2005.

[5] J. Kleijn, M. Koutny, G. Rozenberg, "Towards a Petri Net Semantics for Membrane Systems," *In Proceedings of the WMC6 2005, July 18-21*, Wien, Austria, pp. 439-459, 2005.

[6] Gh. Paun, "Membrane Computing. An Introduction," *Natural computing Series. ed. G. Rozenberg, Th. Back, A.E. EibenJ.N. Kok, H.P. Spaink, Leiden Center for Natural Computing*, Springer-Verlag, Berlin, p. 420, 2002.

[7] Z. Qi, J. You, and H. Mao, "P Systems and Petri Nets," *Proceedings WMC 2003, Lecture Notes in Computer Science, vol. 2933*, Springer-Verlag, Berlin, pp. 387-403, 2003.

Emilian Guţuleac,
Technical University of Moldova,
Computer Science Department,
Address: 168, Bd. Stefan cel Mare, MD-2004,
Chişinău, Republic of Moldova
E-mail: egutuleac@mail.utm.md

ICCCC 2006

The second edition of the International Conference on Computers, Communications & Control[1], ICCCC 2006, was organized by Agora University of Oradea and was powered by IEEE Computer Society, Romania Section, and took place in Baile Felix - Oradea, Romania, June 1-3, 2006.

ICCCC 2006 provides a forum for scientist in academia and industry to present and discuss their latest research findings on a broad array of topics in Computer Science, Information Technology & Data Communications and Computer-based Control.

The scope of the conference covered the following topics: Artificial Intelligence, Automata and Formal Languages, Computational Mathematics, Cryptography and Security, E-Activities, Fuzzy Systems, Informatics in Control, Information Society - Knowledge Society, Natural Computing, Network Design & Internet Services, Multimedia & Communications, Parallel and Distributed Computing.

ICCCC 2006 and the the International Journal of Computers, Communications & Control (IJCCC, founded by I. Dziţac - Executive Editor, F.G. Filip - Editor in Chief and M.J. Manolescu - Managing Editor), celebrates, by two invited papers[2] published in IJCCC Vol. I, No. 1, 100 years from the birth of Grigore C. Moisil (1906-1973). Grigore C. Moisil was one of the great Romanian mathematicians who had a great impact in Computer Science. He received post-mortem, in 1996, the "Computer Pioneer Award" of IEEE Computer Society. He insisted and helped in the building of the first Romanian computer, by Victor Toma, at the Institute of Atomic Physics (1957). He also directed the first generation of graduate students in Mathematics to work with the team of Victor Toma, at the Institute of Atomic Physics; they were trained to learn programming at the new computers CIFA. He introduced Łukasiewicz algebras with three values and multiple values (which are known today as Łukasiewicz-Moisil algebras) and used them in the logic and study of commutation circuits. He developed new methods of analysis for finite automata and had valuable contributions in the filed of algebraic theory of automated mechanism.

The Program Committee received 142 submissions, originating from Algeria, France, Germany, Greece, Hungary, Italy, Japan, India, Ireland, Iran, Spain, Serbia & Montenegro, Moldova, Romania, Thailand, Tunisia and and USA. Each submission was reviewed by two Program Committee members, or other experts. Out of the 142 papers only 91 (64%) were accepted for presentation at the conference and for publication (7 papers in IJCCC, Vol. I (2006), No.1 and 84 papers in this supplementary issue of IJCCC).

The Program Committee gratefully acknowledges all authors who submitted papers for theirs efforts in maintaining the scientific standards of the second edition of ICCCC .

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Ioan Dziţac, Florin G. Filip, Mişu-Jan Manolescu
Conference Chairs

[1] The first edition of this conference, entitled "International Conference on Computers and Communications", ICCC 2004, has been founded and organized in 2004 by I. Dziţac, C. Popescu and H. Oros.

[2] "Grigore C. Moisil (1906 - 1973) and his School in Algebraic Logic", authors George Georgescu, Afrodita Iorgulescu, Sergiu Rudeanu and "Grigore C. Moisil: A Life Becoming A Myth", author Solomon Marcus

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Formation Control of Mobile Robots

Dang Binh Nguyen, Khac Duc Do

Abstract: A constructive method is presented to design cooperative controllers that force a group of N mobile robots to achieve a particular formation in terms of shape and orientation while avoiding collisions between themselves. The control development is based on new local potential functions, which attain the minimum value when the desired formation is achieved, and are equal to infinity when a collision occurs. The proposed controller development is also extended to formation control of nonholonomic mobile robots.
Keywords: Formation control, mobile robot, local potential function, nonholonomic mobile robot.

1 Introduction

Over the last few years, formation control of multiple vehicles has received a lot of attention from the control community. Applications of vehicle formation control include the coordination of multiple robots, unmanned air/ocean vehicles, satellites, aircraft and spacecraft [1]-[28]. For example, a cooperative mobile sensor network, where each mobile robot serves as a mobile sensor, is expected to outperform a single large vehicle with multiple sensors or a collection of independent vehicles when the objective is to climb the gradient of an environmental field. The single, heavily equipped vehicle may require considerable power to operate its sensor payload, it lacks robustness to vehicle failure and it cannot adapt the configuration or resolution of the sensor array. An independent vehicle with a single sensor may need to perform costly maneuvers to effectively climb a gradient, for instance, wandering significantly to collect rich enough data much like the "run and tumble" behavior of flagellated bacteria. In military missions, a group of autonomous vehicles are required to keep in a specified formation for area coverage and reconnaissance. In automated highway system, the throughput of the transportation network can be greatly increased if vehicles can form to platoons at a desired velocity while keeping a specified distance between vehicles. Research on formation control also helps people to better understand some biological social behaviors, such as swarm of insects and flocking of birds.

In the literature, there have been roughly three methods to formation control of multiple vehicles: leader-following, behavioral and virtual structure. Each method has its own advantages and disadvantages. In the leader-following approach, some vehicles are considered as leaders, whist the rest of robots in the group act as followers [1], [2], [3], [4]. The leaders track predefined reference trajectories, and the followers track transformed versions of the states of their nearest neighbors according to given schemes. An advantage of the leader-following approach is that it is easy to understand and implement. In addition, the formation can still be maintained even if the leader is perturbed by some disturbances. However, a disadvantage is that there is no explicit feedback to the formation, that is, no explicit feedback from the followers to the leader in this case. If the follower is perturbed, the formation cannot be maintained. Furthermore, the leader is a single point of failure for the formation. In the behavioral approach [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], few desired behaviors such as collision/obstacle avoidance and goal/target seeking are prescribed for each vehicle and the formation control is calculated from a weighting of the relative importance of each behavior. The advantages of this approach are: it is natural to derive control strategies when vehicles have multiple competing objectives, and an explicit feedback is included through communication between neighbors. The disadvantages are: the group behavior cannot be explicitly defined, and it is difficult to analyze the approach mathematically and guarantee the group stability. In the virtual structure approach, the entire formation is treated as a single entity [15], [16], [17], [18]. When the structure moves, it traces out desired trajectories for each robot in the group to

track. Some similar ideas based on the perceptive reference frame, the virtual leader, and the formation reference point are given in [14], [17], [19]. The advantages of the virtual structure approach are: it is fairly easy to prescribe the coordinated behavior for the group, and the formation can be maintained very well during the manoeuvres, i.e. the virtual structure can evolve as a whole in a given direction with some given orientation and maintain a rigid geometric relationship among multiple vehicles. However requiring the formation to act as a virtual structure limits the class of potential applications such as when the formation shape is time-varying or needs to be frequently reconfigured, this approach may not be the optimal choice. The virtual structure and leader-following approaches require that the full state of the leader or virtual structure be communicated to each member of the formation. In contrast, behavior-based approach is decentralized and may be implemented with significantly less communication. Formation feedback has been recently introduced in the literature [18], [20], [21], [22]. In [18], a coordination architecture for spacecraft formation control is introduced to incorporate the leader-following, behavioral, and virtual structure approaches to the multi-robot coordination problem. This architecture can be extended to include formation feedback. In [20], a Lyapunov formation function is used to define a formation error for a class of robots (double integrator dynamics) so that a constrained motion control problem of multiple systems is converted into a stabilization problem for one single system. The error feedback is incorporated to the virtual leader through parameterized trajectories. In terms of information from the robots in the group used for feedback in the control design for each robot, there are two main approaches to solve the problem of motion planning/control of a group of mobile robots: centralization and decentralization. In the centralized approach, see for example [18], a single controller and collision free trajectories are constructed in a workspace. The centralized approach has a drawback of computation complexity but guarantees a complete solution. The decentralized approach, see for example [23], requires less computational effort, and offers an easy way to scale the size of the robot group. This approach usually involves a combination of robot based local potential fields [14], [24], [25].

The main problem with the decentralized approach is that it is unable or extremely difficult to predict and control the critical points. Basically, the closed loop system under a controller designed by the decentralized approach has multiple equilibrium points. It is rather difficult to design a controller such that all the equilibrium points except for the desired equilibrium one are unstable/saddle points for a group of many robots. Moreover even the formation control system is designed in a centralized manner, the tuning constants in several aforementioned papers (e.g. [26], [27], [28], [29]), which are crucial to guarantee that the only desired equilibrium points are asymptotic stable and that the other critical points are unstable, are extremely difficult to obtain for practical implementation. In most of the above papers, point-robots with simple (single or double integrator) dynamics (e.g. [14], [24], [29]) or fully actuated vehicles [19] (which can be converted to a double integrator dynamics via a feedback linearization) were investigated. Vehicles with nonholonomic constraints were also considered (e.g. [5]). However, the nonholonomic kinematics are transformed to a double integrator dynamics by controlling the hand position instead of the inertial position of the vehicles. Consequently, the vehicle heading is not controlled. In addition, in the tracking control of single nonholonomic mobile robots (e.g. [30], [31], [32]) the tracking errors are often converted into special forms to deal with nonholonomic constraints using several non-trivial coordinate transformations. If these techniques are migrated to formation control of a group of nonholonomic mobile robots, it is extremely difficult to incorporate collision avoidance between the robots. The above problems motivate the contribution of this paper.

In this paper, we propose a constructive method to design a cooperative formation control system for a group of N mobile robots. The simple point-mass robots are first considered to clarify the design philosophy. The proposed technique is extended to mobile robots with nonholonomic constraints (nonholonomic mobile robots). New local potential functions are constructed to design gradient based cooperative controllers to achieve almost global asymptotic convergence of a group of mobile robots to a particular formation in term of both shape and orientation, and guarantee no collisions between themselves. Formal proof of the results is given.

2 Problem statement

We consider a group of N simple point-mass mobile robots, of which each has the following dynamics

$$\dot{q}_i = u_i, \;\; i = 1,...,N \tag{1}$$

where $q_i \in \mathrm{R}^n$ and $u_i \in \mathrm{R}^n$ are the state and control input of the robot i. We assume that $n > 1$ and $N > 1$. The assumption that each robot is represented as a point is not as restrictive as it may seem since various shapes can be mapped to single points through a series of transformations [26], [27], [28]. Our task is to design the control input u_i for each robot i that forces the group of N robots to stabilize with respect to their group members in configurations that make a particular formation specified by a desired vector $l(\eta) = [l_{12}^T(\eta), l_{23}^T(\eta), ..., l_{N-1,N}^T(\eta)]^T$, where $\eta \in \mathrm{R}^m$ is the formation parameter vector to specify the formation change, while avoiding collisions between themselves. The parameter vector η is used to specify rotation, expansion and contraction of the formation such that when η converges to its desired value η_f, the desired shape of the formation is achieved. In addition, it requires all the robots align their velocity vectors to a desired bounded one $u_d \in \mathrm{R}^n$, and move toward specified directions specified by the desired formation velocity vector. The control objective is formally stated as follows:

Control objective: Assume that at the initial time t_0 each robot initializes at a different location, and that each robot has a different desired location, i.e. there exist strictly positive constants ε_1, ε_2 and ε_3 such that

$$\begin{array}{l} ||q_i(t_0) - q_j(t_0)|| \geq \varepsilon_1, \\ ||l_{ij}(\eta)|| \geq \varepsilon_2, \\ ||\partial l_{ij}(\eta)/\partial \eta|| \leq \varepsilon_3, \; \forall i, j \in \{1,2,...N\}, \; \forall \eta \in \mathrm{R}^m. \end{array} \tag{2}$$

Design the control input u_i for each robot i , and an update law for the formation parameter vector η such that each robot (almost) globally asymptotically approaches its desired location to form a desired formation, and that the robots' velocity converges to the desired (bounded) velocity u_d while avoiding collisions with all other robots in the group, i.e.

$$\begin{array}{l} \lim_{t\to\infty}(q_i(t) - q_j(t) - l_{ij}(\eta(t))) = 0, \\ \lim_{t\to\infty}(\eta(t) - \eta_f) = 0, \\ \lim_{t\to\infty}(u_i(t) - u_d) = 0, \\ ||q_i(t) - q_j(t)|| > \varepsilon_4, \; \forall i, j \in \{1,2,...N\}, \; \forall t \geq t_0 \geq 0 \end{array} \tag{3}$$

where ε_4 is a strictly positive constant, and η_f is a vector of constants that determine the desired formation. The desired formation can be represented by a labeled directed graph ([29], [34]) in the following definition.

Definition 1. The formation graph, $G = \{V, E, L\}$ is a directed labeled graph consisting of:

-a set of vertices (nodes), $V = \{\vartheta_1, \cdots, \vartheta_N\}$ indexed by the mobile robots in the group,

-a set of edges, $E = \{(\vartheta_i, \vartheta_j) \in V \times V\}$, containing ordered pairs of vertices that represent inter-robot position constraints, and

-a set of labels, $L = \{\gamma_{ij} | \gamma_{ij} = ||q_i - q_j - l_{ij}||^2, \forall (\vartheta_i, \vartheta_j) \in E\}$, $l_{ij} = q_{if} - q_{jf} \in \mathrm{R}^n$ indexed by the edges in E.

Indeed, when the control objective is achieved, the edge labels become $||q_i - q_j - l_{ij}||^2 = 0, \forall (\vartheta_i, \vartheta_j) \in E$, i.e. the relative distance between the robots i and j is l_{ij}.

3 Control design

We consider the following local potential function

$$\varphi_i = \gamma_i + \delta\beta_i \tag{4}$$

where δ are positive tuning constants, the functions γ_i and β_i are the goal and related collision avoidance functions for the robot i specified as follows:

-The goal function γ_i is essentially the sum of all distances from the robot i to its adjacent group members, N_i. A simple choice of this function is

$$\gamma_i = \sum_{j \in N_i} \gamma_{ij}, \qquad \gamma_{ij} = \frac{1}{2}||q_i - q_j - l_{ij}||^2. \tag{5}$$

-The related collision function β_i should be chosen such that it is equal to infinity whenever any robots come in contact with the robot i, i.e. a collision occurs, and attains the minimum value when the robot i is at its desired location with respect to other group members belong to N_i, which are adjacent to the robot i. This function is chosen as follows:

$$\beta_i = \sum_{j \in N_i} \left(\frac{\beta_{ij}^k}{\beta_{ijl}^{2k}} + \frac{1}{\beta_{ij}^k} \right) \tag{6}$$

where k is a positive constant to be chosen later, β_{ij} and β_{ijl} are collision and desired collision functions chosen as

$$\beta_{ij} = \frac{1}{2}||q_i - q_j||^2, \ \beta_{ijl} = \frac{1}{2}||l_{ij}||^2. \tag{7}$$

It is noted from (7) that $\beta_{ij} = \beta_{ji}$ and $\beta_{ijl} = \beta_{jil}$.

Remark 1.

1. The above choice of the potential function φ_i given in (4) with its components specified in (5)-(6), has the following properties: 1) it attains the minimum value when the robot i is at the desired location with respect to other group member belong to N_i, which are adjacent to the robot i, i.e. $q_i - q_j - l_{ij} = 0, \ j \in N_i$, and 2) it is equal to infinity whenever one or more robots come in contact with the robot i, i.e. when a collision occurs.

2. The potential function (4) is different from the ones proposed in [14] and [33] in the sense that the ones in [14] and [33] are centralized and do not put penalty on the relative distance between the robots, i.e. do not include the goal function γ_i. Therefore, the controllers developed in [14] and [33] do not guarantee the formation converge to a specified configuration but to any configurations that locally minimize the potential functions (these potential functions in [14] and [33] are nonconvex).

3. Our potential function (4) is also different from the navigation functions proposed in [26] and [29] in the sense that our potential function is of the form of sum of collision avoidance functions while those navigation functions in [26] and [29] are of the form of product of collision avoidance functions . This feature makes our potential function "more decentralized". Furthermore, our potential function is equal to infinity while those in [14], [26] and [29] is equal to a finite constant when a collision occurs. However, those in [26] and [29] also cover obstacle and work space boundary avoidance. Although these issues are not included in this paper for clarity, considering these issues is possible and is the subject of future work.

4. Our potential function does not have problems like local minima and non-reachable goal as listed in [24].

To design the control input u_i, we differentiate both sides of (4) along the solutions of (1) to obtain

$$\begin{aligned} \dot{\varphi}_i &= \sum_{j \in N_i} [\Omega_{ij}^T (u_i - u_j) - \Psi_{ij}^T \dot{\eta}] \\ &= \sum_{j \in N_i} [\Omega_{ij}^T (u_i - u_d - (u_j - u_d)) - \Psi_{ij}^T \dot{\eta}] \\ &= \sum_{j \in N_i} \Omega_{ij}^T (u_i - u_d) - \sum_{j \in N_i} \Omega_{ij}^T (u_j - u_d) - \sum_{j \in N_i} \Psi_{ij}^T \dot{\eta} \end{aligned} \tag{8}$$

where

$$\begin{aligned}\Omega_{ij} &= q_i - q_j - l_{ij} + \delta k \left(\frac{1}{\beta_{ijl}^{2k}} - \frac{1}{\beta_{ij}^{2k}} \right) \beta_{ij}^{k-1} (q_i - q_j) \\ \Psi_{ij} &= \left[\left(q_i - q_j - l_{ij} + \frac{2\delta k \beta_{ij}^{k}}{\beta_{ijl}^{2k+1}} l_{ij} \right)^T \frac{\partial l_{ij}}{\partial \eta} \right]^T .\end{aligned} \tag{9}$$

From (8), we simply choose the control u_i for the robot i and the update law for η as follows:

$$\begin{aligned}u_i &= -C \sum_{j \in N_i} \Omega_{ij} + u_d \\ \dot{\eta} &= -\Gamma(\eta - \eta_f)\end{aligned} \tag{10}$$

where $C \in \mathrm{R}_+^{n \times n}$ and $\Gamma \in \mathrm{R}_+^{m \times m}$ are symmetric positive definite matrices. Substituting (10) into (8) yields

$$\dot{\varphi}_i = -\sum_{j \in N_i} \Omega_{ij}^T C \sum_{j \in N_i} \Omega_{ij} - \sum_{j \in N_i} \Omega_{ij}^T (u_j - u_d) + \sum_{j \in N_i} \Psi_{ij}^T \Gamma(\eta - \eta_f). \tag{11}$$

Substituting (10) into (1) results in the closed loop system

$$\dot{q}_i = -C \sum_{j \in N_i} \Omega_{ij} + u_d, \; i = 1, ..., N. \tag{12}$$

Since the desired formation is specified in terms on relative distances between the robots, we write the closed loop system of the inter-robot dynamics from the closed loop system (12) as

$$\dot{q}_{ij} = -C \left(\sum_{a \in N_i} \Omega_{ia} - \sum_{b \in N_j} \Omega_{jb} \right), \; (i, j) \in \{1, ..., N\}, \; i \neq j \tag{13}$$

where $q_{ij} = q_i - q_j$. We now state the main result in the following theorem.

Theorem 1. *Under the assumptions stated in the control objective, the control for each robot i given in (10) with an appropriate choice of the tuning constants δ and k, solves the control objective.*

Proof. See Appendix.

4 Simulations

We carry out a simulation example in two-dimensional space to illustrate the results. The number of robots is $N = 4$. The initial positions of robots are chosen randomly in the circle with a radius of 0.5 centered at the origin. The design constants are chosen as $C = diag(0.4, 0.4)$, $k = 0.5$, $\delta = 0.1$. It is noted that this choice satisfies the conditions in the proof of Theorem 1. We run two simulations with $u_d = [1 \; 0.2]^T$ (linear formation motion meaning that each robot will move on a rectilinear line to form the desired formation) and $u_d = [\sin(0.5t) \; \cos(0.5t)]$ (circular formation motion meaning that each robot will move on a circle to form the desired formation). For clarity, we take the formation parameter η as a scalar to implement formation expansion. The desired formation is depicted in Figure 1. These simulations are motivated by gradient climbing missions in which the mobile sensor network (each mobile robot serves as a mobile sensor) seeks out local maxima or minima in the environmental field. The network can adapt its configuration in response to the sensed environment in order to optimize its gradient climb. For example, gradients in temperature fields (among others) can be estimated from the data collected by the

mobile robots; these are of interest for enabling gradient climbing to locate and track features such as fronts and eddies. These gradients can be used to compute the desired reference velocity vector u_d in our simulations in this section. In the first 4.5 seconds (for the linear formation motion case) and 15 seconds (for the circular formation case), η is set to zero then is updated to $\eta_f = 3$ for the rest of simulation time. The update gain is chosen as $\Gamma = 2$ (scalar).

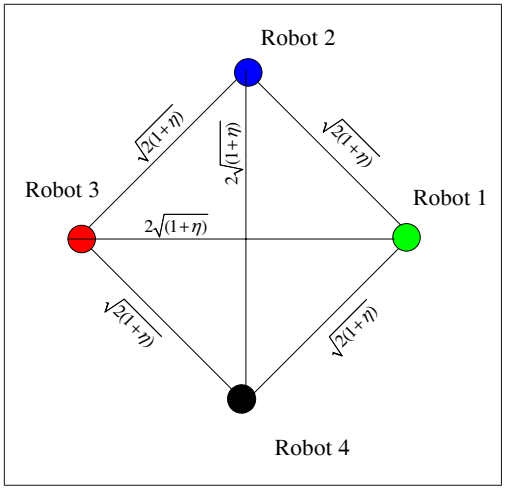

Figure 1: Desired formation for simulation.

Figures 2 and 3 plot simulation results for the linear formation motion and circular formation cases, respectively. For clarity, we only plot the control $u_1 = [u_{x1}\ u_{y1}]^T$ and distances from the robot 1 to other members in the group, i.e. $\|q_{12}\|, \|q_{13}\|$ and $\|q_{14}\|$. It is seen from these figures that the desired formation shapes are nicely achieved and there are no collisions between any robots, see the bottom right figures in Figures 2 and 3, where the distances from the robot 1 to other members in the groups are plotted. Clearly, these distances are always larger than zero. It is also seen from Figures 2 and 3 that at the beginning all the robots rapidly move away from each other to avoid collisions since they start pretty close to each other.

5 Extension to formation control of nonholonomic mobile robots

Control of single nonholonomic mobile robots receives considerable attention, and is complicated due to the fact that they have less controls than the outputs to be controlled, see for example [30], [31], [32] and references therein. Indeed, control of a group of nonholonomic mobile robots is more complicated due to some nonholonomic (non-integral) constraint. However, in this section we show that the control method developed in Section 3 can be readily extended to force a group of N nonholonomic mobile robots of unicycle type to move in such a way that a desired formation is achieved. For clarity, we consider only the kinematic model of the nonholonomic mobile robots. Designing the control system at the dynamic level even without requiring robot velocities be measured can be carried out using one more "backstepping" step [35] and our proposed exponential observer in [31]. Consider the kinematic model of the unicycle mobile robot i, whose only two wheels are actuated and the third wheel is not actuated

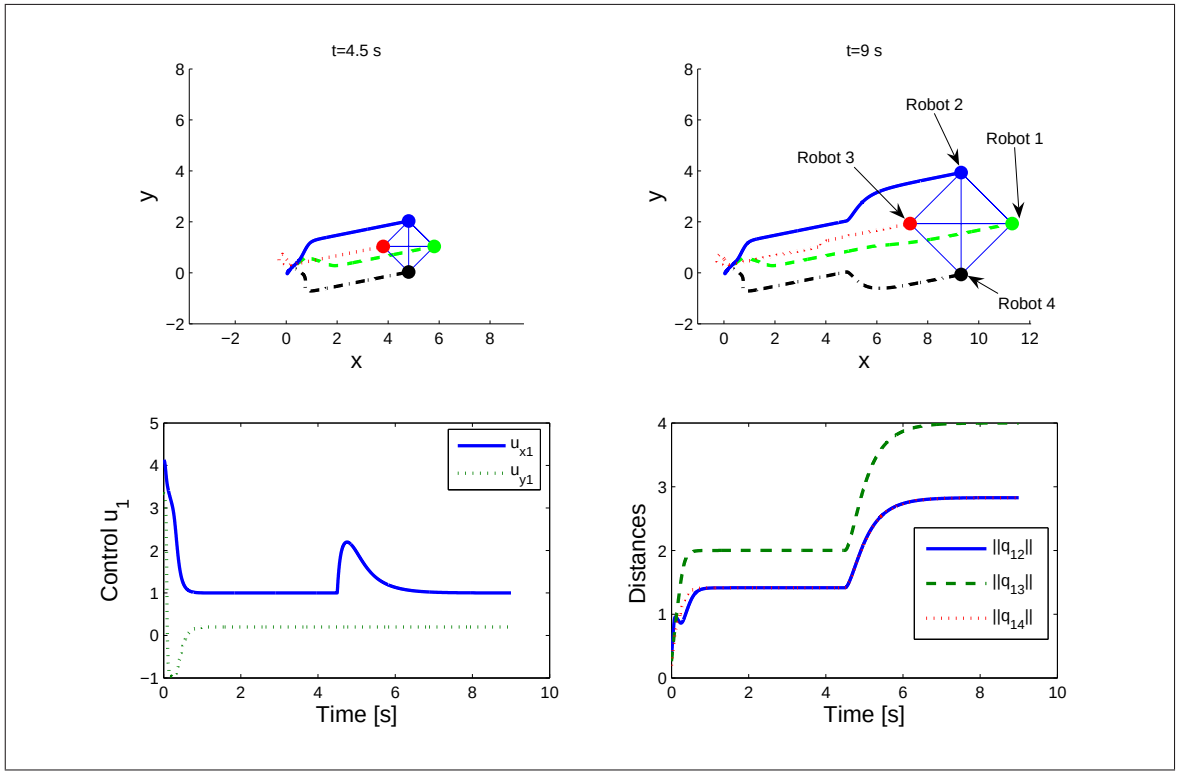

Figure 2: Linear formation motion: simulation results.

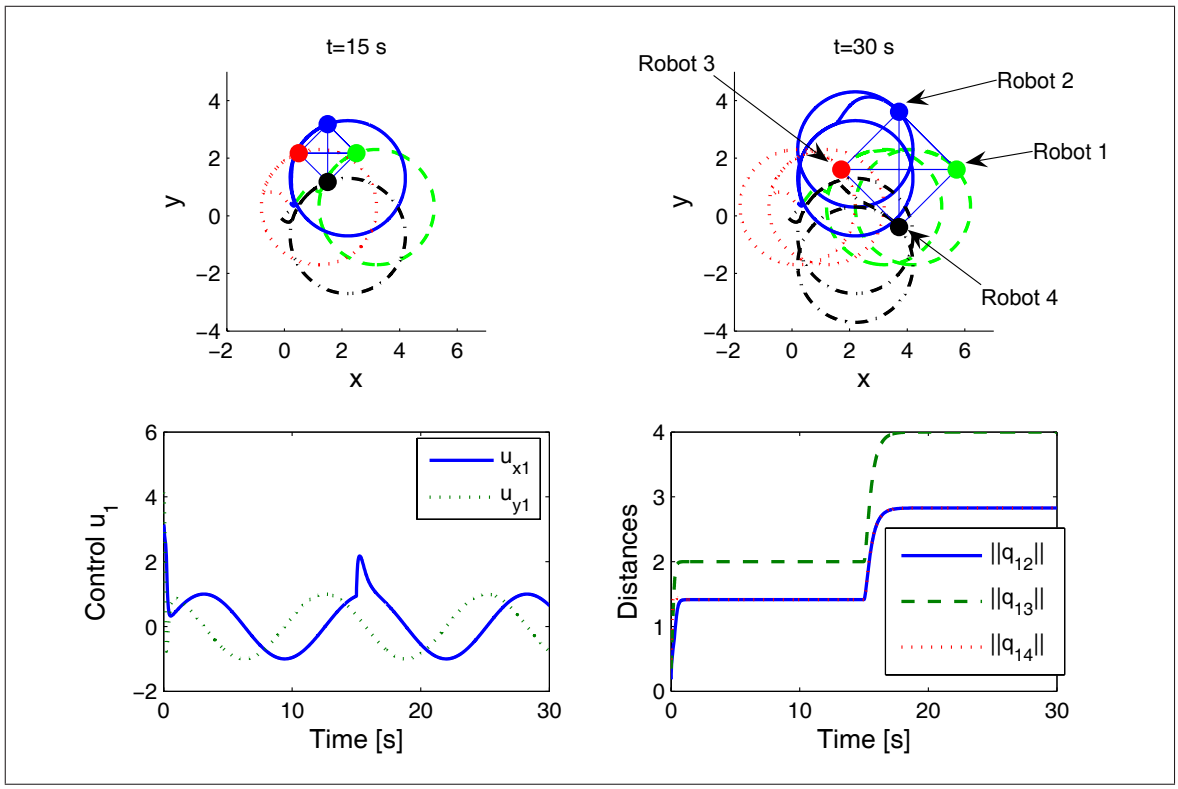

Figure 3: Circular formation motion: simulation results.

(see Figure 4), given by

$$\begin{aligned}\dot{x}_i &= \frac{R_i}{2}(\cos(\theta_i)\omega_{1i} + \cos(\theta_i)\omega_{2i}) \\ \dot{y}_i &= \frac{R_i}{2}(\sin(\theta_i)\omega_{1i} + \sin(\theta_i)\omega_{2i}) \\ \dot{\theta}_i &= \frac{R_i}{2b_i}(\omega_{1i} - \omega_{2i})\end{aligned} \tag{14}$$

where (x_i, y_i) denote the coordinates of the middle point, P_{0i}, between the left and right driving wheels, and θ_i denotes the heading of the robot i coordinated in the earth-fixed frame OXY, see Figure 4, ω_{1i} and ω_{2i} denote the angular velocities of the wheels of the robot i. Moreover R_i and b_i are defined in Figure 4. The task now is to design the control inputs ω_{1i} and ω_{2i} to achieve the control objective stated in Section 3. We require an additional assumption on the desired formation velocity vector u_d that $\lim_{t\to\infty}||u_d(t)|| \neq 0$, i.e. we do not consider the stabilization/regulation problem. For convenience, we convert the angular velocities of the wheels to the linear and angular velocities (v_i and r_i) of the robot i by the following relationship:

$$\begin{bmatrix} v_i \\ r_i \end{bmatrix} = \left(\frac{1}{R_i}\begin{bmatrix} 1 & b_i \\ 1 & -b_i \end{bmatrix}\right)^{-1}\begin{bmatrix} \omega_{1i} \\ \omega_{2i} \end{bmatrix}. \tag{15}$$

With (15), we can write (14) as

$$\begin{aligned}\dot{x}_i &= v_i\cos(\theta_i) \\ \dot{y}_i &= v_i\sin(\theta_i) \\ \dot{\theta}_i &= r_i\end{aligned} \tag{16}$$

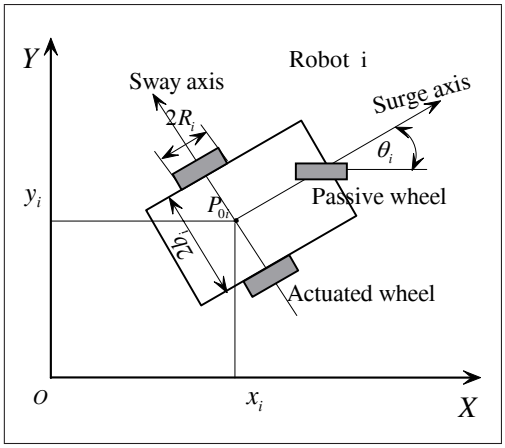

Figure 4: Geometric description of a nonholonomic mobile robot.

Indeed, the kinematic model (14) or (16) possesses the following nonholonomic constraint:

$$\dot{x}_i\sin(\theta_i) - \dot{y}_i\cos(\theta_i) = 0. \tag{17}$$

Moreover, we will consider the the linear and angular velocities (v_i and r_i) of the robot i as the control inputs. After these inputs are designed, ω_{1i} and ω_{2i} are calculated from (15).

5.1 Control design

The control design consists of two steps. At the first step, we consider the control v_i and the yaw angle θ_i as a virtual control to steer the robot position (x_i, y_i) to its desired location. At the second step, the control r_i will be desired to force the virtual yaw angle to converge to its actual yaw angle.

Step 1. Define

$$\theta_{ei} = \theta_i - \alpha_{\theta_i} \tag{18}$$

where α_{θ_i} is a virtual control of θ_i. With (18), we can write (16) as

$$\dot{q}_i = u_i + \Lambda_{\theta_{ei}} \tag{19}$$

where

$$q_i = \begin{vmatrix} x_i \\ y_i \end{vmatrix},\ u_i = \begin{vmatrix} \cos(\alpha_{\theta_i}) \\ \sin(\alpha_{\theta_i}) \end{vmatrix} v_i,\ \Lambda_{\theta_{ei}} = \begin{vmatrix} (\cos(\theta_{ei})-1)\cos(\alpha_{\theta_i}) - \sin(\theta_{ei})\sin(\alpha_{\theta_i}) \\ \sin(\theta_{ei})\cos(\alpha_{\theta_i}) + (\cos(\theta_{ei})-1)\sin(\alpha_{\theta_i}) \end{vmatrix} v_i. \tag{20}$$

It is seen that (19) is almost of the same form as (1). However, the problem is that the controls v_i and α_{θ_i} are not solvable directly from the control u_i if u_i is not designed properly. We therefore present briefly how u_i is designed to tackle that problem. Consider the following potential function (the same form as (4))

$$\varphi_i = \gamma_i + \delta\beta_i \tag{21}$$

where δ, γ_i and β_i are defined in Section 3, see (6) and (7). Differentiating both sides of (21) along the solutions of (19) gives

$$\dot{\varphi}_i = \sum_{j\in N_i} [\Omega_{ij}^T(u_i + \Lambda_{\theta_{ei}} - u_d^* - (u_j + \Lambda_{\theta_{ej}} - u_d^*)) - \Psi_{ij}^T\dot{\eta}] \tag{22}$$

where Ω_{ij} and Ψ_{ij} are defined in (9), and $u_d^* = \sqrt{1 + \sum_{i=1}^{N} || \sum_{j\in N_i} \Omega_{ij}||^2}\, u_d$. It is noted that we use u_d^* instead of u_d in (22) to overcome the nonholonomic problem of the mobile robot under investigation. Indeed, $\lim_{t\to\infty} \sum_{j\in N_i} \Omega_{ij}(t) = 0$ implies that $\lim_{t\to\infty} u_d^*(t) = u_d$. From (22), we choose the control u_i and the update law for η as

$$\begin{aligned} u_i &= -C||u_d|| \sum_{j\in N_i} \Omega_{ij} + u_d^* \\ \dot{\eta} &= -\Gamma(\eta - \eta_f) \end{aligned} \tag{23}$$

where C and Γ are diagonal positive definite matrices. Again, $||u_d||$ is included in the control u_i to overcome the nonholonomic problem. Defining $\theta_d = \arctan(u_{dy}/u_{dx})$, then from the first equations of (23) and (20), we have

$$\begin{aligned} \cos(\alpha_{\theta_i})v_i &= -c_1||u_d|| \sum_{j\in N_i} \Omega_{xij} + \sqrt{1 + \sum_{i=1}^{N} || \sum_{j\in N_i} \Omega_{ij}||^2}||u_d||\cos(\theta_d) \\ \sin(\alpha_{\theta_i})v_i &= -c_2||u_d|| \sum_{j\in N_i} \Omega_{yij} + \sqrt{1 + \sum_{i=1}^{N} || \sum_{j\in N_i} \Omega_{ij}||^2}||u_d||\sin(\theta_d) \end{aligned} \tag{24}$$

where Ω_{xij} and Ω_{yij} are defined as $\Omega_{ij} = [\Omega_{xij}\ \Omega_{yij}]^T$, c_1 and c_2 are defined as $C = diag(c_1, c_2)$. We now need to solve (24) for v_i and α_{θ_i}. To do this, multiplying both sides of the first and second equations of (24) with $\cos(\theta_d)$ and $\sin(\theta_d)$, respectively, then adding them together result in

$$\begin{aligned} \cos(\alpha_{\theta_i} - \theta_d)v_i = \quad & -c_1||u_d|| \sum_{j\in N_i} \Omega_{xij}\cos(\theta_d) - \\ & c_2||u_d|| \sum_{j\in N_i} \Omega_{yij}\sin(\theta_d) + \sqrt{1 + \sum_{i=1}^{N} || \sum_{j\in N_i} \Omega_{ij}||^2}||u_d||. \end{aligned} \tag{25}$$

On the other hand, multiplying both sides of the first and second equations of (24) with $\sin(\theta_d)$ and $\cos(\theta_d)$, respectively, then subtracting from each other result in

$$\sin(\alpha_{\theta_i}-\theta_d)v_i = c_1||u_d||\sum_{j\in N_i}\Omega_{xij}\sin(\theta_d) - c_2||u_d||\sum_{j\in N_i}\Omega_{yij}\cos(\theta_d). \tag{26}$$

From (25) and (26), we have

$$\alpha_{\theta_i} = \theta_d + \arctan\left(\frac{c_1\sum\limits_{j\in N_i}\Omega_{xij}\sin(\theta_d) - c_2\sum\limits_{j\in N_i}\Omega_{yij}\cos(\theta_d)}{-c_1\sum\limits_{j\in N_i}\Omega_{xij}\cos(\theta_d) - c_2\sum\limits_{j\in N_i}\Omega_{yij}\sin(\theta_d) + \sqrt{1+\sum\limits_{i=1}^{N}||\sum\limits_{j\in N_i}\Omega_{ij}||^2}}\right). \tag{27}$$

It is seen that (27) is well-defined if the positive constants c_1 and c_2 are chosen such that

$$c_1 + c_2 < 1. \tag{28}$$

The control v_i is found by solving (24) as

$$\begin{aligned} v_i = \cos(\alpha_{\theta_i})||u_d||\left(-c_1\sum_{j\in N_i}\Omega_{xij} + \sqrt{1+\sum_{i=1}^{N}||\sum_{j\in N_i}\Omega_{ij}||^2}\cos(\theta_d)\right) + \\ \sin(\alpha_{\theta_i})||u_d||\left(-c_2\sum_{j\in N_i}\Omega_{yij} + \sqrt{1+\sum_{i=1}^{N}||\sum_{j\in N_i}\Omega_{ij}||^2}\sin(\theta_d)\right). \end{aligned} \tag{29}$$

Substituting (23) into (22) results in

$$\dot{\varphi}_i = -||u_d||\sum_{j\in N_i}\Omega_{ij}^T C\sum_{j\in N_i}\Omega_{ij} + \sum_{j\in N_i}[\Omega_{ij}^T(\Lambda_{\theta_{ei}} - (u_j + \Lambda_{\theta_{ej}} - u_d^*)) + \Psi_{ij}^T\Gamma(\eta-\eta_f)]. \tag{30}$$

Step 2. To design the control r_i, differentiating both sides of (18) along the solutions of the third equation of (16) and choosing the control r_i as

$$r_i = -d_i\theta_{ei} - \dot{\alpha}_{\theta_i} - \sum_{j\in N_i}\Omega_{ij}^T\Lambda_{\theta_{ei}}/\theta_{ei} \tag{31}$$

where d_i is a positive constant, and the term $\sum\limits_{j\in N_i}\Omega_{ij}^T\Lambda_{\theta_{ei}}/\theta_{ei}$ is to cancel the cross term $\sum\limits_{j\in N_i}\Omega_{ij}^T\Lambda_{\theta_{ei}}$ in (30), result in

$$\dot{\theta}_{ei} = -d_i\theta_{ei} - \sum_{j\in N_i}\Omega_{ij}^T\Lambda_{\theta_{ei}}/\theta_{ei}. \tag{32}$$

Note that $\Lambda_{\theta_{ei}}/\theta_{ei}$ is well defined since $\sin(\theta_{ie})/\theta_{ie} = \int\limits_0^1\cos(\theta_{ie}\lambda)d\lambda$ and $(\cos(\theta_{ie})-1)/\theta_{ie} = \int\limits_0^1\sin(\theta_{ie}\lambda)d\lambda$ are smooth functions.

4.2 Stability analysis

We consider the following function

$$\varphi_{tot} = \log(1+\sum_{i=1}^{N}(\varphi_i+\theta_{ei}^2)) + \frac{1}{2}(\eta-\eta_f)^T\Gamma(\eta-\eta_f) \tag{33}$$

whose derivative along the solutions of (30), (32) and the second equation of (23) satisfies

$$\dot{\varphi}_{tot} = -2\frac{||u_d||\sum\limits_{i=1}^{N}\sum\limits_{j\in N_i}\Omega_{ij}^T C\sum\limits_{j\in N_i}\Omega_{ij} + \sum\limits_{i=1}^{N}d_i\theta_{ei}^2}{1+\sum\limits_{i=1}^{N}(\varphi_i+\theta_{ei}^2)} + \frac{\sum\limits_{i=1}^{N}\sum\limits_{j\in N_i}\Psi_{ij}^T\Gamma(\eta-\eta_f)}{1+\sum\limits_{i=1}^{N}(\varphi_i+\theta_{ei}^2)} - (\eta-\eta_f)^T\Gamma(\eta-\eta_f) \tag{34}$$

where we have used

$$-\sum_{i=1}^{N}\sum_{j\in N_i}[\Omega_{ij}^T(u_j+\Lambda_{\theta_{ej}}-u_d^*) = \sum_{i=1}^{N}\sum_{j\in N_i}[\Omega_{ij}^T(u_i-u_d^*+\Lambda_{\theta_{ei}})$$

$$= -||u_d||\sum_{i=1}^{N}\sum_{j\in N_i}\Omega_{ij}^T C\sum_{j\in N_i}\Omega_{ij}+\sum_{i=1}^{N}\sum_{j\in N_i}\Omega_{ij}^T\Lambda_{\theta_{ei}}. \quad (35)$$

The rest of stability analysis can be carried out in the same lines as in Proof of Theorem 1 since (34) is of the same form as (40) and $\lim_{t\to\infty}||u_d(t)|| \neq 0$ by assumption. Finally, note that $\lim_{t\to\infty}\theta_{ei}(t)=0$ and $\lim_{t\to\infty}\sum_{j\in N_i}\Omega_{ij}(t)=0$ implies that $\lim_{t\to\infty}(\theta_i(t)-\theta_d)=0$, i.e. the yaw angle of all robots converge to the desired angle $\theta_d = \arctan(u_{dy}/u_{dx})$.

5.2 Simulation results

We now perform a simulation to illustrate the results in the previous subsection. The number of robots, initial conditions of the robot positions, control gains, desired formation velocity and desired formation shape are the same as in Section 4. The robot heading angles are initialized randomly in the circle with a radius of 0.5 centered at the origin. For clarity, we only simulate the circular formation motion, and we do not include simulation results on the formation expansion as in Section 4, i.e. the formation parameter η is set to zero in all the simulation time. The other design constants are chosen as $d_i = 5$. Simulation results are plotted in Figure 5. Again, it is seen that the robots are forced to move to nicely achieve the desired formation and no collisions between the robots occur. Moreover, the yaw angle of all robots converges to the desired value θ_d, see the top-right figure in Figure 5, where the yaw angle errors are plotted. A close look at Figure 5 shows that the main different between simulation results in this subsection and those in Section 4 is that the robots take a longer time to approach the desired formation. This is because we use the heading angles θ_i as the virtual controls to steer the robots to overcome the noholonomic constraint.

6 Summary and Conclusions

This paper has contributed the method to construct local potential functions, based on which gradient-like cooperative controllers were designed for a group of mobile robots both with and without nonholonomic constraints to perform certain formation missions. Formal analysis of the convergence and feasibility of the control solutions have also been provided. In the near future, it is of interest to apply the proposed control design method combined with the control design scheme for other single underactuated robots with second order nonholonomic constraints such as underactuated ships [37] to achieve a desired formation for a group of underactuated systems.

7 Appendix: Proof of Theorem 1

We prove Theorem 1 in two steps. At the first step, we show that there are no collisions between any robots and the solutions of the closed loop system exist. At the second step, we prove that the equilibrium point of the inter-robot dynamics closed loop system (13), at which $q_i - q_j - l_{ij} = 0$, is asymptotically stable. Finally, we show that all other equilibrium(s) of (13) are either unstable or saddle.

Step 1. Proof of no collision and existence of solutions:

We consider the following common potential function φ given by

$$\varphi = \sum_{i=1}^{N}\varphi_i \quad (36)$$

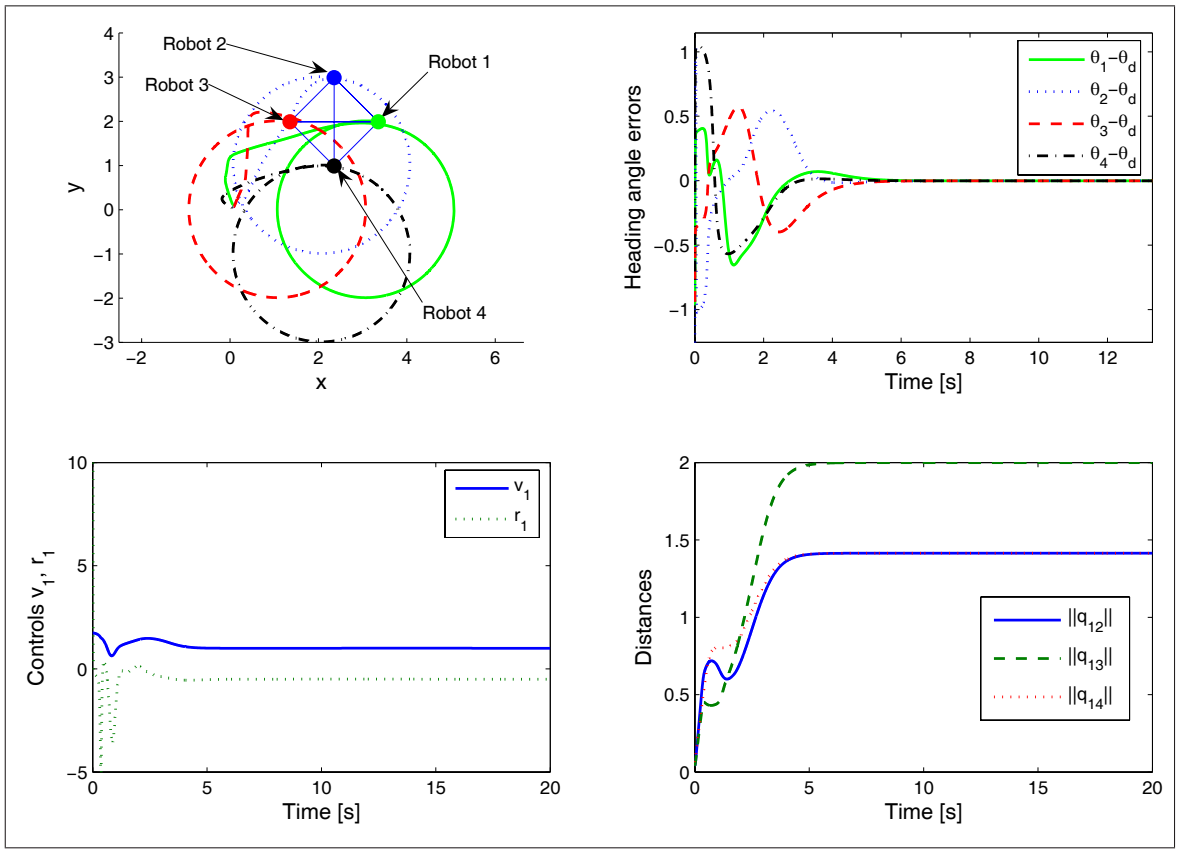

Figure 5: Mobile robot circular formation motion: simulation result.

whose derivative along the solutions of (11) is

$$\dot{\varphi} = -\sum_{i=1}^{N}\sum_{j\in N_i}\Omega_{ij}^T C\sum_{j\in N_i}\Omega_{ij} - \sum_{i=1}^{N}\sum_{j\in N_i}\Omega_{ij}^T(u_j-u_d) + \sum_{i=1}^{N}\sum_{j\in N_i}\Psi_{ij}^T\Gamma(\eta-\eta_f). \tag{37}$$

Since $l_{ij} = -l_{ji}$ and $\Omega_{ij} = -\Omega_{ji}$, we have

$$\sum_{i=1}^{N}\sum_{j\in N_i}\Omega_{ij}^T(u_j-u_d) = -\sum_{i=1}^{N}\sum_{j\in N_i}\Omega_{ij}^T(u_i-u_d). \tag{38}$$

Substituting (38) into (37) gives

$$\dot{\varphi} = -2\sum_{i=1}^{N}\sum_{j\in N_i}\Omega_{ij}^T C\sum_{j\in N_i}\Omega_{ij} + \sum_{i=1}^{N}\sum_{j\in N_i}\Psi_{ij}^T\Gamma(\eta-\eta_f). \tag{39}$$

We now consider the following total function $\varphi_{tot} = \log(1+\varphi) + 0.5||\eta-\eta_f||^2$ whose derivative along the solutions of (39) the second equation of (10) satisfies

$$\dot{\varphi}_{tot} = -\frac{2}{1+\varphi}\sum_{i=1}^{N}\sum_{j\in N_i}\Omega_{ij}^T C\sum_{j\in N_i}\Omega_{ij} + \frac{1}{1+\varphi}\sum_{i=1}^{N}\sum_{j\in N_i}\Psi_{ij}^T\Gamma(\eta-\eta_f) - (\eta-\eta_f)^T\Gamma(\eta-\eta_f) \tag{40}$$

which implies that

$$\begin{aligned}\dot{\varphi}_{tot} \leq \quad & -\frac{2}{1+\varphi}\sum_{i=1}^{N}\sum_{j\in N_i}\Omega_{ij}^T C\sum_{j\in N_i}\Omega_{ij} + \frac{\lambda_{\max}(\Gamma)}{4\varepsilon(1+\varphi)^2}\left\|\sum_{i=1}^{N}\sum_{j\in N_i}\Psi_{ij}^T\right\|^2 - \\ & (\lambda_{\min}(\Gamma) - \varepsilon\lambda_{\max}(\Gamma))||\eta-\eta_f||^2\end{aligned} \tag{41}$$

where ε is a positive constant, $\lambda_{\min}(\Gamma)$ and $\lambda_{\max}(\Gamma)$ denote the minimum and maximum eigenvalues of Γ respectively. From (9), and definition of the function φ, it can be readily shown that there exists a positive constant $\omega_{\max}$ such that

$$\frac{1}{(1+\varphi)^2}\left\|\sum_{i=1}^{N}\sum_{j\in N_i}\Psi_{ij}^T\right\|^2 \leq \omega_{\max} \tag{42}$$

With (42) in mind, picking $\varepsilon = \lambda_{\min}(\Gamma)/\lambda_{\max}(\Gamma)$ we can write (41) as

$$\dot{\varphi}_{tot} \leq \frac{\lambda_{\max}^2(\Gamma)}{4\lambda_{\min}(\Gamma)}\omega_{\max} \triangleq \varpi_{\max}. \tag{43}$$

Integrating both sides of (43) results in

$$\varphi_{tot}(t) \leq \varphi_{tot}(t_0) + \varpi_{\max}(t-t_0). \tag{44}$$

where $\varphi_{tot}(t)$ and $\varphi_{tot}(t_0)$ are (from the definition of φ_{tot})

$$\begin{aligned}\varphi_{tot}(t) &= \log\left[1+\sum_{i=1}^{N}\left(\gamma_i(t)+\delta\sum_{j\in N_i}\left(\frac{\beta_{ij}^k(t)}{\beta_{ijl}^{2k}}+\frac{1}{\beta_{ij}^k(t)}\right)\right)\right] + \tfrac{1}{2}||\eta(t)-\eta_f||^2 \\ \varphi_{tot}(t_0) &= \log\left[1+\sum_{i=1}^{N}\left(\gamma_i(t_0)+\delta\sum_{j\in N_i}\left(\frac{\beta_{ij}^k(t_0)}{\beta_{ijl}^{2k}}+\frac{1}{\beta_{ij}^k(t_0)}\right)\right)\right] + \tfrac{1}{2}||\eta(t_0)-\eta_f||^2.\end{aligned} \tag{45}$$

The right hand side of (44) cannot escape to infinity unless when $t=\infty$ since $\beta_{ijl} > 0$ and $\beta_{ij}(t_0) > 0$ (see definition of β_{ijl} and β_{ij} given in (7)). Therefore the left hand side of (44) cannot escape to infinity for

all $t \in [t_0, \infty)$. This implies that $\beta_{ij}(t)$ cannot be zero for all $t \in [t_0, \infty)$, i.e. no collisions can occur for all $t \in [t_0, \infty)$. On the other hand, it is true from the second equation of (10) that

$$||\eta(t) - \eta_f|| \leq ||\eta(t_0) - \eta_f|| e^{-\lambda_{\min}(\Gamma)(t-t_0)} \tag{46}$$

which means that the desired formation shape is achieved exponentially. Using (42) and (46), we can write (41) as

$$\dot{\varphi}_{tot} \leq \lambda_{\max}(\Gamma)\sqrt{\omega_{\max}}||\eta(t_0) - \eta_f|| e^{-\lambda_{\min}(\Gamma)(t-t_0)}. \tag{47}$$

Integrating both sides of (47) from t_0 to t results in

$$\varphi_{tot}(t) \leq \varphi_{tot}(t_0) + \lambda_{\max}(\Gamma)\sqrt{\omega_{\max}}||\eta(t_0) - \eta_f||/\lambda_{\min}(\Gamma). \tag{48}$$

It is seen that the right hand side of (48) is bounded. Therefore the left hand side of (48) must also be bounded. This implies that $\beta_{ij}(t)$ must be larger than a strictly positive constant for all $t \in [t_0, \infty)$, which in turn means that there exists a strictly positive constant ε_4 such that the last inequality of (3) holds. To prove that the solutions of the closed loop system (12) exist, we consider the function $W = 0.5\sum_{i=1}^{N}||q_i||^2$ whose derivative along the solutions of (12), after some simple manipulation, satisfies $\dot{W} \leq \rho_1(1+1/\min(\beta_{ij}))W + \rho_2$, where ρ_1 and ρ_2 are some positive constants, which implies that the solutions of (12) exist since $\beta_{ij}(t)$ is larger than a strictly positive constant for all $t \in [t_0, \infty)$. Furthermore, applying Barbalat's lemma found in [36] to (41) gives

$$\lim_{t\to\infty} \frac{1}{1+\varphi(t)} \sum_{i=1}^{N} \sum_{j\in N_i} \Omega_{ij}^T(t) C \sum_{j\in N_i} \Omega_{ij}(t) = 0 \tag{49}$$

which implies that

$$\begin{cases} \lim_{t\to\infty} \sum\limits_{j\in N_i} \Omega_{ij}(t) = 0 \\ \lim_{t\to\infty} \varphi(t) = \chi_1 \end{cases} \quad \text{or} \quad \begin{cases} \lim_{t\to\infty} \sum\limits_{j\in N_i} \Omega_{ij}(t) = \chi_2 \\ \lim_{t\to\infty} \varphi(t) = \infty \end{cases} \tag{50}$$

where χ_1 and χ_2 are some constants. From definitions of Ω_{ij} and φ, the second limit set in (50) cannot be true. Therefore, the first limit set in (50) implies that $\lim_{t\to\infty} \sum\limits_{j\in N_i} \Omega_{ij}(t) = 0$.

Step 2. Behavior near equilibrium points.

At the steady state, the equilibrium points are found by solving the following equations

$$\sum_{j\in N_i} \Omega_{ij} = \sum_{j\in N_i} \left(q_{ij} - l_{ij} + \delta k \left(\frac{1}{\beta_{ijl}^{2k}} - \frac{1}{\beta_{ij}^{2k}} \right) \beta_{ij}^{k-1} q_{ij} \right) = 0,\ i = 1, ..., N. \tag{51}$$

It is directly verified that $\bar{q} = \bar{l}$ where $\bar{q}$ and are stack vectors of q_{ij} and l_{ij}, respectively, i.e. $\bar{q} = [q_{12}^T, q_{13}^T ..., q_{N-1,N}^T]^T$ and $\bar{l} = [l_{12}^T, l_{13}^T ..., l_{N-1,N}^T]^T$, is one root of (51). In addition there is (are) another root(s) denoted by $\bar{q}_c = [q_{12c}^T, q_{13c}^T ..., q_{N-1,Nc}^T]^T$ of (51) different from $\bar{l}$ satisfying

$$\sum_{j\in N_i} \Omega_{ij}\Big|_{\bar{q}=\bar{q}_c} = \sum_{j\in N_i} \left(q_{ijc} - l_{ij} + \delta k \left(\frac{1}{\beta_{ijl}^{2k}} - \frac{1}{\beta_{ijc}^{2k}} \right) \beta_{ijc}^{k-1} q_{ijc} \right) = 0,\ i = 1, ..., N \tag{52}$$

where $\beta_{ijc} = 0.5||q_{ic} - q_{jc}||^2$. In the following, we will show that the equilibrium point $\bar{q} = \bar{l}$ is asymptotically stable, and the equilibrium point(s) $\bar{q} = \bar{q}_c$ is (are) unstable or saddle. We now write the closed loop system of the inter-robot dynamics (13) as

$$\dot{\bar{q}} = -\bar{C}\bar{F}(\bar{q}, \bar{l}). \tag{53}$$

where $\bar{C} = diag(\underbrace{C,\cdots,C}_{E})$ with E the number of edges of the formation graph, and

$$F(\bar{q},\bar{l}) = [\sum_{a\in N_1}\Omega_{1a}^T - \sum_{b\in N_2}\Omega_{2b}^T, \sum_{a\in N_1}\Omega_{1a}^T - \sum_{b\in N_3}\Omega_{3b}^T, ..., \sum_{a\in N_i}\Omega_{ia}^T - \sum_{b\in N_j}\Omega_{jb}^T, ..., \sum_{a\in N_{N-1}}\Omega_{N-1,a}^T - \sum_{b\in N_N}\Omega_{Nb}^T]^T. \quad (54)$$

Since (52) holds for all $i = 1,...,N$, at the steady state we have $\sum_{a\in N_i}\Omega_{ia} - \sum_{b\in N_j}\Omega_{jb} = 0,\ \forall(i,j)\in\{1,...,N\},\ i \neq j$. Therefore the equilibrium points $\bar{q} = \bar{l}$ and $\bar{q} = \bar{q}_c$ are also the equilibrium points of (53). The general gradient of $F(\bar{q},\bar{l})$ with respect to $\bar{q}$ is given by

$$\frac{\partial F(\bar{q},\bar{l})}{\partial \bar{q}} = \begin{bmatrix} \frac{\partial \Xi_{12}}{\partial q_{12}} & \frac{\partial \Xi_{12}}{\partial q_{13}} & \cdots & \frac{\partial \Xi_{12}}{\partial q_{N-1,N}} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial \Xi_{ij}}{\partial q_{12}} & \cdots & \frac{\partial \Xi_{ij}}{\partial q_{ij}} & \frac{\partial \Xi_{ij}}{\partial q_{N-1,N}} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial \Xi_{N-1,N}}{\partial q_{12}} & \cdots & \cdots & \frac{\partial \Xi_{N-1,N}}{\partial q_{N-1,N}} \end{bmatrix},$$
$$\Xi_{ij} = \sum_{a\in N_i}\Omega_{ia} - \sum_{b\in N_j}\Omega_{jb},\ (i,j)\in\{1,...,N\},\ i\neq j. \quad (55)$$

It can be checked that

$$\begin{aligned} \frac{\partial \Xi_{ij}}{\partial q_{ij}} &= NI_{n\times n} + 2\delta k\left(\frac{1}{\beta_{ijl}^{2k}} - \frac{1}{\beta_{ij}^{2k}}\right)\beta_{ij}^{k-1}I_{n\times n} + 2\delta k\left((k-1)\left(\frac{1}{\beta_{ijl}^{2k}} - \frac{1}{\beta_{ij}^{2k}}\right)\beta_{ij}^{k-2} + \frac{2k}{\beta_{ij}^{k+2}}\right)q_{ij}q_{ij}^T \triangleq H_{ij} \\ \frac{\partial \Xi_{ij}}{\partial q_{cd}} &= s\delta k\left(\frac{1}{\beta_{cdl}^{2k}} - \frac{1}{\beta_{cd}^{2k}}\right)\beta_{cd}^{k-1}I_{n\times n} + s\delta k\left((k-1)\left(\frac{1}{\beta_{cdl}^{2k}} - \frac{1}{\beta_{cd}^{2k}}\right)\beta_{cd}^{k-2} + \frac{2k}{\beta_{cd}^{k+2}}\right)q_{cd}q_{cd}^T, \end{aligned} \quad (56)$$

where $(c,d)\in\{1,...,N\},\ (c,d)\neq(i,j), c\neq d$, and $s = 1$ or $s = -1$ depending on value of c, d, i and j. However, we do not need to specify the sign of s for our next task. We now investigate properties of the equilibrium points $\bar{q} = \bar{l}$ and $\bar{q} = \bar{q}_c$ based on the general gradient $\partial F(\bar{q},\bar{l})/\partial\bar{q}$ evaluated at those points.

Step 2.1 Proof of $\bar{q} = \bar{l}$ being the asymptotic stable equilibrium point:
At the equilibrium point $\bar{q} = \bar{l}$, we have

$$\left.\frac{\partial \Xi_{ij}}{\partial q_{ij}}\right|_{\bar{q}=\bar{l}} = NI_{n\times n} + \frac{4\delta k^2}{\beta_{ijl}^{k+2}}l_{ij}l_{ij}^T,\quad \left.\frac{\partial \Xi_{ij}}{\partial q_{cd}}\right|_{\bar{q}=\bar{l}} = s\frac{2\delta k^2}{\beta_{cdl}^{k+2}}l_{cd}l_{cd}^T, \quad (57)$$

where $\beta_{cdl} = 0.5||l_{cd}||^2$. With (57), let $\xi\in \mathrm{R}^{nE}$ we have

$$\xi^T\left.\frac{\partial F(\bar{q},\bar{l})}{\partial\bar{q}}\right|_{\bar{q}=\bar{l}}\xi \geq \left(N - \frac{4\delta k^2 nE\max(l_{ija}^2)}{\min(\beta_{ijl}^{k+2})}\right)\xi^T\xi,\ (i,j)\in\{1,...,N\},\ i\neq j \quad (58)$$

where l_{ija} is the a^{th} element of l_{ij}. Therefore, for any given constant k if we choose the tuning constant δ such that

$$N - \frac{4\delta k^2 nE\max(l_{ija}^2)}{\min(\beta_{ijl}^{k+2})} > 0 \rightarrow\ \delta < \frac{N\min(\beta_{ijl}^{k+2})}{4k^2 nE\max(l_{ija}^2)},\ (i,j)\in\{1,...,N\},\ i\neq j \quad (59)$$

then the matrix $\partial F(\bar{q},\bar{l})/\partial\bar{q}|_{\bar{q}=\bar{l}}$ is positive definite, which in turn implies that the equilibrium point $\bar{q} = \bar{l}$ is asymptotically stable.

Step 2.2. Proof of $\bar{q}=\bar{q_c}$ *being the unstable/saddle equilibrium point(s):* The idea is to consider block matrices on the main diagonal of the matrix $\partial F(\bar{q},\bar{l})/\partial\bar{q}\big|_{\bar{q}=\bar{q_c}}$ and show that there exists at least one block matrix whose determinant is negative. Define $H_{ijc}=\partial\Xi_{ij}/\partial q_{ij}\big|_{\bar{q}=\bar{q_c}}$ and let ϕ_a and ϕ_b be the a^{th} and b^{th} elements of q_{ijc}, $(a,b)\in\{1,...,n\}$, $a\neq b$. We form the matrices H_{ijc}^{ab} from the matrix H_{ijc} as follows

$$H_{ijc}^{ab}=\begin{bmatrix} h_{11} & h_{12}\\ h_{21} & h_{22}\end{bmatrix}$$

$$\begin{aligned}
h_{11}&=N+2\delta k\Pi_{ijc}\beta_{ijc}^{k-1}+2\delta k[(k-1)\Pi_{ijc}\beta_{ijc}^{k-2}+2k/\beta_{ijc}^{k+2}]\phi_a^2\\
h_{12}&=2\delta k[(k-1)\Pi_{ijc}\beta_{ijc}^{k-2}+2k/\beta_{ijc}^{k+2}]\phi_a\phi_b\\
h_{21}&=2\delta k[(k-1)\Pi_{ijc}\beta_{ijc}^{k-2}+2k/\beta_{ijc}^{k+2}]\phi_a\phi_b\\
h_{22}&=N+2\delta k\Pi_{ijc}\beta_{ijc}^{k-1}+2\delta k[(k-1)\Pi_{ijc}\beta_{ijc}^{k-2}+2k/\beta_{ijc}^{k+2}]\phi_b^2
\end{aligned}\tag{60}$$

where $\Pi_{ijc}=1/\beta_{ijl}^{2k}-1/\beta_{ijc}^{2k}$. The determinant of H_{ijc}^{ab} is given by

$$\det(H_{ijc}^{ab})=(N+2\delta k\Pi_{ijc}\beta_{ijc}^{k-1})\Delta_{ijc}^{ab}\tag{61}$$

where

$$\Delta_{ijc}^{ab}=N+2\delta k\Pi_{ijc}\beta_{ijc}^{k-1}+2\delta k[(k-1)\Pi_{ijc}\beta_{ijc}^{k-2}+2k/\beta_{ijc}^{k+2}](\phi_a^2+\phi_b^2)\tag{62}$$

Let us consider the sum:

$$\sum_{a=1}^{n-1}\sum_{b=a+1}^{n}\Delta_{ijc}^{ab}=n(n-1)N+2\delta k(n-1)(2(k-1)+n)\beta_{ijc}^{k-1}/\beta_{ijl}^{2k}+2\delta k(n-1)(2(k+1)-n)/\beta_{ijc}^{k+1}.\tag{63}$$

Since $n>1$, picking $k>n/2-1$ ensures that $\sum\limits_{a=1}^{n-1}\sum\limits_{b=a+1}^{n}\Delta_{ijc}^{ab}>0$. Therefore, there exists at least one pair $(a,b)\in\{1,...,n\}$ denoted by (a^*,b^*) such that $\Delta_{ijc}^{a^*b^*}>0$. Now for all $(i,j)\in\{1,...,N\}$, $i\neq j$ let us consider the sum:

$$\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{\det(H_{ijc}^{a^*b^*})}{\Delta_{ijc}^{a^*b^*}}\beta_{ijc}=\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}(N\beta_{ijc}+2\delta k\Pi_{ijc}\beta_{ijc}^{k}).\tag{64}$$

On the other hand, multiplying both sides of $F(\bar{q_c},\bar{l})=0$ with $\bar{q_c}^T$ results in $\bar{q_c}^TF(\bar{q_c},\bar{l})=0$, which is expanded to

$$\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}(Nq_{ijc}^T(q_{ijc}-l_{ij})+2\delta kN\Pi_{ijc}\beta_{ijc}^{k})=0.\tag{65}$$

Substituting (65) into (64) results in

$$\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{\det(H_{ijc}^{a^*b^*})}{\Delta_{ijc}^{a^*b^*}}\beta_{ijc}=\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}(N-2)\beta_{ijc}+\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}q_{ijc}^Tl_{ij}.\tag{66}$$

The term $\sum\limits_{i=1}^{N-1}\sum\limits_{j=i+1}^{N}\left(q_{ijc}^Tl_{ij}\right)$ is strictly negative since at the point where $q_{ij}=l_{ij}$ (the point F in Figure 6) all attractive and repulsive forces are equal to zero while at the point where $q_{ij}=q_{ijc}$ (the point C in Figure 6) the sum of attractive and repulsive forces is equal to zero (see Section 2 for discussion of a simple case). Therefore the point $q_{ij}=0$ (the point O in Figure 6) must locate between the points $q_{ij}=l_{ij}$ and $q_{ij}=q_{ijc}$, see Figure 6. Furthermore if we write (65) as

$$2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\beta_{ijc}+\delta k(\beta_{ijc}^{k}/\beta_{ijl}^{2k}-1/\beta_{ijc}^{k})=\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}q_{ijc}^Tl_{ij}\tag{67}$$

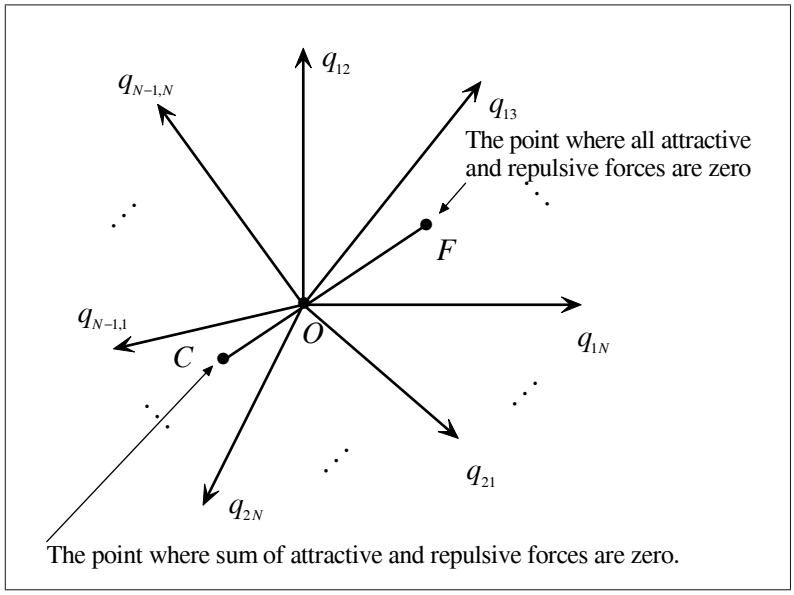

Figure 6: Illustration of location of critical points.

we can see that deceasing δ results in decrease in β_{ijc} since β_{ijl} is a bounded constant and the right hand side of (67) is negative. Therefore, choosing a sufficiently small δ ensures that the right hand of (64) is strictly negative since $\beta_{ijc} = 0.5||q_{ijc}||^2$. That is

$$\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{\det(H_{ijc}^{a^*b^*})}{\Delta_{ijc}^{a^*b^*}}\beta_{ijc} < 0 \tag{68}$$

which implies that there exists at least one pair $(i,j) \in \{1,...,N\}$ denoted by (i^*, j^*) such that

$$\det(H_{i^*j^*c}^{a^*b^*}) < 0. \tag{69}$$

The inequality implies that at least one eigenvalue of the matrix $\partial F(\bar{q},\bar{l})/\partial\bar{q}\big|_{\bar{q}=\bar{q}_c}$ is negative. This in turn guarantees that $\bar{q}_c$ is an unstable/saddle equilibrium point of (53). Proof of Theorem 1 is completed.

References

[1] P. K. C. Wang, Navigation Strategies for Multiple Autonomous Mobile Robots Moving in Formation, *J. Robot. Syst.*, Vol. 8, No. 2, pp. 177-195, 1991.

[2] P. K. C. Wang and F. Y. Hadaegh, Coordination and Control of Multiple Microspacecraft Moving in Formation, *J. Astronautical Sci.*, Vol. 44, No. 3, pp. 315-355, 1996.

[3] J. P. Desai, J. Ostrowski, and V. Kumar, Controlling Formations of Multiple Mobile Robots, *Proc. IEEE Int. Conf. Robotics and Automation*, Leuven, Belgium, pp. 2864-2869, 1998.

[4] M. Mesbahi and F. Y. Hadaegh, Formation Flying Control of Multiple Spacecraft via Graphs, Matrix Inequalities, and Switching, *AIAA J. Guidance, Control, Dynam.*, Vol. 24, no. 2, pp. 369-377, 2000.

[5] R. T. Jonathan, R. W. Beard and B. J. Young, A Decentralized Approach to Formation Maneuvers, *IEEE Trans. Robot. and Automat.*, Vol. 19, pp. 933-941, 2003.

[6] T. D. Barfoot and C. M. Clark, Motion Planning for Formations of Mobile Robots, *Robot. Auton. Syst.*, vol. 46, pp. 65-78, 2004.

[7] H. Yamaguchi, Adaptive Formation Control for Distributed Autonomous Mobile Robot Groups, *Proc. IEEE Int. Conf. Robotics and Automation, Albuquerque*, NM, pp. 2300-2305, 1997.

[8] T. Balch and R. C. Arkin, Behavior-Based Formation Control for Multirobot Teams, *IEEE Trans. Robot. Automat.*, Vol. 14, pp. 926-939, 1998.

[9] M. Schneider-Fontan and M. J. Mataric, Territorial Multirobot Task Division, *IEEE Trans. Robot. Automat.*, Vol. 14, pp. 815-822, 1998.

[10] Q. Chen and J. Y. S. Luh, Coordination and Control of a Group of Small Mobile Robots, *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 2315-2320, 1994.

[11] M. Veloso, P. Stone, and K. Han, The CMUnited-97 Robotic Soccer Team: Perception and Multi-agent Control, *Robot. Auton. Syst.*, Vol. 29, pp. 133-143, 1999.

[12] L. E. Parker, ALLIANCE: An Architecture for Fault-tolerant Multirobot Cooperation, *IEEE Trans. Robot. Automat.*, Vol. 14, pp. 220-240, 1998.

[13] K. Sugihara and I. Suzuki, Distributed Algorithms for Formation of Geometric Patterns with Many Mobile Robots, *J. Robot. Syst.*, Vol. 13, no. 3, pp. 127-139, 1996.

[14] N. E. Leonard and E. Fiorelli, Virtual Leaders, Artificial Potentials and Coordinated Control of Groups, *Proc. IEEE Conf. Decision and Control*, Orlando, FL, pp. 2968-2973, 2001.

[15] W. Kang, N. Xi, and A. Sparks, Formation Control of Autonomous Agents in 3D Workspace, *Proc. IEEE Int. Conf. Robotics and Automation*, San Francisco, CA, pp. 1755-1760, 2000.

[16] M. A. Lewis and K.-H. Tan, High Precision Formation Control of Mobile Robots Using Virtual Structures, *Auton. Robots*, Vol. 4, pp. 387-403, 1997.

[17] W. Kang and H.-H. Yeh, Coordinated Attitude Control of Multisatellite Systems, *Int. J. Robust Nonlinear Control*, Vol.12, pp. 185-205, 2002.

[18] R. W. Beard, J. Lawton, and F. Y. Hadaegh, A Coordination Architecture for Formation Control, *IEEE Trans. Control Syst. Technol.*, Vol. 9, pp. 777-790, 2002.

[19] R. Skjetne, S. Moi and T. I. Fossen, Nonlinear Formation Control of Marine Craft, *Proc. IEEE Conf. on Decision and Control*, Las Vegas, NV, pp. 1699-1704, 2002.

[20] P. Ogren, M. Egerstedt and X. Hu, A Control Lyapunov Function Approach to Multiagent Coordination, *IEEE Trans. Robot. Autom.* Vol.18, pp. 847-851.

[21] W. Ren and R. W. Beard, Formation Feedback Control for Multiple Spacecraft via Virtual Structures. *IEE Proceedings-Control Theory Application*, Vol. 151, pp. 357-368, 2004.

[22] E. W. Jush and P. S. Krishnaprasad, Equilibria and Steering Laws for Planar Formations, *Syst. Contr. Letters*, Vol. 52, pp. 25-38, 2004.

[23] D. M. Stipanovica, G. Inalhana, R. Teo and C. J. Tomlina, Decentralized overlapping control of a formation of unmanned aerial vehicles, *Automatica*, vol. 40, pp. 1285-1296, 2004.

[24] S. S. Ge and Y. J. Cui, New Potential Functions for Mobile Robot Path Planning, *IEEE Trans. Robot. Automat.*, Vol. 16, pp. 615-620, 2000.

[25] S. S. Ge and Y. J. Cui, Dynamics Motion Planning for Mobile Robots using Potential Field Method, *Auton. Robots*, Vol. 13, pp. 207-222, 2000.

[26] E. Rimon and D.E. Koditschek, Exact Robot Navigation Using Artificial Potential Functions, *IEEE Trans. Robot. and Automat.*, Vol. 8, no. 5, pp. 501-518, 1992.

[27] E. Rimon and D.E. Koditschek, Robot Navigation Functions on Manifolds with Boundary, *Advances in Applied Mathematics*, Vol. 11, pp. 412-442, 1990.

[28] H. G. Tanner, S. G. Loizou and K. J. Kyriakopoulos, Nonholonomic Navigation and Control of Multiple Mobile Robot Manipulators, *IEEE Trans. Robot. Automat.*, Vol. 19, no. 1, pp. 53-64, 2003.

[29] H.G. Tanner and A. Kumar, Towards Decentralization of Multi-robot Navigation Functions, *IEEE Int. Conf. Robotics and Automation*, Barcelona, Spain, pp 4143-4148, 2005.

[30] W. E. Dixon, D. M. Dawson, E. Zergeroglu and A. Behal, *Nonlinear Control of Wheeled Mobile Robots*, Springer, London, 2001.

[31] K. D. Do, Z. P. Jiang and J. Pan, A Global Output-feedback Controller for Simultaneous Tracking and Stabilization of Mobile Robots, *IEEE Trans. Robot. Automat.*, Vol.20, pp. 589-584, 2004.

[32] T. Fukao, H. Nakagawa, and N. Adachi, Adaptive tracking control of nonholonomic mobile robot, *IEEE Trans. Robot. Automat.*, Vol. 16, pp. 609-615, 2000.

[33] H. G. Tanner, A. Jadbabaie and G. J. Pappas, Stable Flocking of Mobile Agents, Part I: Fixed Topology, *Proc. IEEE Conf. Decision and Control*, Hawaii, pp. 2010-2015, 2003.

[34] G. Godsils and G. Royle, *Algebraic Graph Theory*, New York: Springer Graduate Texts in Mathematics, 207, 2001.

[35] M. Krstic, I. Kanellakopoulos and P.V. Kokotovic, *Nonlinear and Adaptive Control Design*, New York: Wiley, 1995.

[36] H. Khalil, *Nonlinear Systems*, Prentice Hall, 2002.

[37] K. D. Do and J. Pan, Global Path-tracking of Underactuated Ships with Non-zero Off-diagonal Terms, *Automatica*, Vol. 41, pp. 87-95, 2005.

Dang Binh Nguyen
Thai Nguyen University of Technology
Rector's Office
3-2 Street, Thai Nguyen City, Vietnam
E-mail: nguyen.d.binh.tnut@gmail.com
Khac Duc Do
School of Mechanical Engineering
The University of Western Australia
35 Stirling Highway, Crawley, WA 6009, Australia
E-mail: duc@mech.uwa.edu.au

CESA 2006

The Multiconference on “Computational Engineering in Systems Applications” (CESA 2006), co-sponsored by IMACS (the International Association for Mathematics and Computers in Simulation) and IEEE/SMC Society, has been held in Beijing on 4-6 October 2006. Its aim was to bring together scholars and practitioners from academia and industries to exchange the latest development in theories, and applications of computational techniques.

Over the last decades, it has become a strong need for exchange on common computational and algorithmic tools between researchers working in different application backgrounds. Under this situation, the first CESA conference (CESA 96) was successfully held in Lille, France in July 1996. The following two conferences CESA98 and CESA 2003 were held in Nabeul-Hammamet, Tunisia in April 1998 and in Lille in July 2003 respectively.

CESA 2006 has been organized at the prestigious Tsinghua University and was co-chair by the Professors Pierre Borne (from the Ecole Centrale de Lille, France) and Bo Zhang (from the Tsinghua University, China). The co-chairs of the International Program Committee was Professors Xianyi Zeng (from the Ecole Nationale des Arts et Industries Textiles, France) and Shiqing Yang (from the Tsinghua University, China). The local program committee chair was Professor Fun Chun Sun.

During this conference 388 communications have been presented which correspond to an acceptation ratio of a little more than one paper on three.

Five very will known scientists have presented exciting plenary lectures :

- "A Computational Systems Approach to Urban Disruption", by Professor James Tien from the Resselaer Polytechnic Institute (USA)
- "A Hybrid Intelligent Optimal Control Method for the Whole Production Line and Applications", by Professor Tiannyou Chai form the Northeastern University (China)
- "Computer-Aided Decision-Making: Systems, Applications and Modern Solutions", by Professor Florin Gheorghe Filip, Vice-President of the Romanian Academy, (Romania)
- "Multimodal Integration and Learning in Cognitive Technical Systems ", by Professor Jianwei Zhang from the University of Hamburg (Germany)
- "Modeling and Control of Multi-Locomotion Robots", by Professor Toshio Fukuda from the Nagoya University (Japan)

The banquet of the conference has been organized on October Tuesday 5, in the famous and well known Summer Palace were a beautiful spectacle in the pure Chinese tradition has been offered to the conference participants.

During CESA 2006 various new and we hope fruitful collaborations have been initialized between participants.

Pierre Borne, Conference Chair

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Bringing IPTV to the Market through Differentiated Service Provisioning

Cathryn Peoples, Petre Dini, Sally McClean, Gerard Parr, Michaela Black

Abstract:
The world of telecommunications continues to provide radical technologies. Offering the benefits of a superior television experience at reduced long-term costs, IPTV is the newest offering. Deployments, however, are slow to be rolled out; the hardware and software support necessary is not uniformly available.
This paper examines the challenges in providing IPTV services and the limitations in developments to overcome these challenges. Subsequently, a proposal is made which attempts to help solve the challenge of fulfilling real-time multimedia transmissions through provisioning for differentiated services. Initial implementations in Opnet are documented, and the paper concludes with an outline of future work.
Keywords: Transport layer, real-time communication, QoS, multimedia protocols, reconfigurable stacks, Opnet simulation.

1 Introduction

It is anticipated that IPTV will be enthusiastically accepted [1] [2; cited by 4] by early adopters, those with a passion for technology. However, while the desire for rich multimedia-based information grows, it is necessary to remove any service impairments to maximise the possibilities of widespread attraction. IPTV, with its high bandwidth and strict Quality of Service (QoS) requirements, will currently not operate to a satisfactory quality in many networks throughout the world. Investments and improvements are therefore required.

The potential for IPTV to become a killer application will depend on such developments. Without an efficient and reliable service, demand for it cannot grow. As with previous Internet applications with widespread demand, it is anticipated that IPTV will have a similar appeal. The race is now on to make the necessary hardware and software upgrades to ensure an end-user experience of quality.

2 IPTV

A report by Accenture [3] revealed that there is a lack of consumer awareness on the definition of IPTV. For those who claim to understand, some exhibited widely varying interpretations. In the context of this paper, it is our (the authors') understanding that IPTV describes the transmission of traditional television over an IP network. In addition, IPTV seeks to further build upon the user experience. The intention is to enable a customised and interactive service [4] [5]. It will be possible to search for on-demand viewing, obtain access to exclusive content, and succumb to product recommendation.

To attract initial customers, it is not thought imperative to provide a service which is fully reliable or which exceeds the current viewing experience. In the early stages, IPTV is likely to be used as a supplement to the traditional television service, adopted by those with a passion for new technologies. However, to ensure longevity, it is necessary to provide a service which exceeds the current experience. This demands a service which is uninterrupted, reliable, and ideally offers cost advantages. In addition, availability through minimal operational efforts is advantageous in terms of encouraging widespread appeal.

2.1 Challenges of Transmitting IPTV

There are numerous challenges to providing IPTV. Voice and video are applications with stringent QoS requirements, demanding an end-to-end delay of less than 100 milliseconds and a bit error rate (BER) of less than 10^{-6}. In addition, they require minimal variation on the amount of end-to-end delay; jitter has a negative effect on the ability to stream the service smoothly. Indeed, the accumulation of a sufficient amount can render the communication useless [6].

Ensuring high levels of QoS is difficult, especially given the increasing popularity of the Internet and resulting pressure on restricted resources. In addition, increased roll-out of wireless links creates connections with notoriously error-prone links. Rejaie et al (1999) [7] have the opinion that, "the quality of delivered service to real-time operations is neither controllable nor predictable." While this fact may have been true in 1999, developments are ongoing to remove the occurrence of such limited network performance. The ability to achieve certainty in the reliability and quality of transmissions is required. Customers purchase Internet packages according to different levels of QoS, which guarantee that they will receive a certain level of performance. Therefore, the ability to ensure the quality of a real-time service is required.

3 Multimedia Protocols

Numerous multimedia protocols have been designed in recent years to meet the challenges involved in achieving real-time communication. In addition to considering those developed specifically for multimedia transmissions, protocols with rate-based control mechanisms are also applicable to multimedia transmissions. Flow control is an important attribute where applications require a steady rate of throughput and where reliability is required. Window-based flow control, as in the case of TCP [8], is inappropriate for multimedia applications. Variable file sizes result in transportation through the network at different rates. Setting a retransmission time-out which does not match the time-out appropriate to the media can increase jitter, and hence QoS. In addition, rate-based transport protocols are considered to be more reliable than window-based approaches. The design of the window-based approach is highly constrained in terms of window-size and retransmission time-out, and any changes in the external environment will cause the protocol to fail. Rate-based approaches, in contrast, adapt based on real-time, and not pre-defined, information.

The Broadband Application Transport System (BATS) [9] was proposed in 1994 as a rate-based transport protocol. Supporting four classes of service, provisions are made for a variety of application requirements. While ensuring throughput of Class A applications (those which are time-sensitive, connection-oriented, and which require a constant bit rate) by blocking all subsequent communications, there is a limitation of this approach in terms of coping ability when there is more than one Class A transmission. As all connections are blocked when a Class A application is transmitting to ensure sufficient bandwidth, the implication is that a second Class A transmission must wait until the first has completed. This approach, therefore, has significant limitations.

RT-Ring [10] was developed in 2002 to transmit multimedia in real-time. It offers three qualities of service and a fairness control mechanism which provisions for traffic with both real-time and non real-time requirements. However, a limitation also exists with this approach. The principle behind this protocol is that a non-satisfied station (one which has not achieved its real-time transmission) can maintain priority until it is satisfied. What happens, however, if there are multiple stations with the same priority? In large-scale deployments, this approach is likely to be unsuitable.

The Rate Adaptation Protocol (RAP) [7] was created to provide QoS for multimedia applications by adapting the quality of a flow of data. Quality is adapted by using layered encoding, and simultaneously delivering a number of layers which can fit inside the available bandwidth. However, despite the benefits of bandwidth-provisioning, doubts exist regarding the direct provisions made for the transmission of

real-time traffic. Each packet is acknowledged and losses are detected by missing ACKs. Lost data is not retransmitted, but the information is used to update the rate at which traffic flows. In addition, RAP incorporates a feature of adapting the rate of flow depending on the feedback delay. Adjusting the rate of flow does not seem like a suitable response to take for video applications, where such actions will result in varying amounts of network jitter.

The Rate Control Scheme (RCS) is designed for environments with high error rates and high bandwidth-delay products. It uses dummy packets to perform congestion control and an AMID algorithm to adjust its transmission rate. A flaw exists in this protocol in relation to its approach to flow and congestion control. Due to the protocol's inability to perform retransmissions, if congestion occurs between a dummy packet being received at the source and the actual transmission being sent, the data will be lost without the ability to be recovered. In addition, it appears as though this protocol could cause the application to experience variable jitter. If a dummy packet is not received, the transmission will cease at least until the period when the next dummy segment is to be sent. Providing sufficient bandwidth exists, the transmission will continue. However, a gap in the transmission will have been introduced, and bringing with it jitter.

A QoS-Guaranteed Transport System (QTS) [11] provides differentiated QoS based on the needs of the application. A bandwidth allocator determines the rate at which data is transported through the network, and the transport protocol module performs rate-based congestion control at a rate which has been determined by the bandwidth allocator. As with BATS, the limitation is that there is no mechanism to cope with multiple applications having the same QoS requirements. It therefore seems difficult to ensure that applications will receive the required QoS.

The main criticism of the current protocols which have been developed for multimedia applications is that they do not take network resource information into account when making protocol choices. While the QoS requirements of the application are important, there are benefits in also incorporating network information. In this way, the available resources can be maximised for all applications and not only those with Class A (in BATS [9] language) requirements.

3.1 Reliable Transportation from the Application or Transport Layer?

It is appropriate at this stage to discuss the location of transportation reliability within the protocol stack. Provisions for transmission reliability are increasingly being incorporated within the application layer. The Real-Time Protocol (RTP) [12] is one such example, used in the application layer of the OSI (Open Systems Interconnection) [13] protocol stack for the transmission of applications with real-time requirements. CFDP [14], the CCSDS [15] File Delivery Protocol developed by the Delay Tolerant Network Research Group (DTNRG) [16], is another example, deployed within the CCSDS protocol stack [17]. Flow and error control functions are combined within the application layer in an attempt to compress the layered approach to solving the communication problem as introduced by the ISO (International Standards Organisation) [18]. However, it is the opinion of the authors that it makes greater sense to retain the traditional layered approach to solving the communication problem, and have each layer solve an individually complex problem. This explains why the protocols under investigation are located within the transport, and not the application, layer.

4 Reconfigurable Protocol Stacks

The concept of reconfigurable protocol stacks has long been under investigation [19] [20] [21], and it is believed that there are significant performance improvements to be achieved in the real-time multimedia transmission challenge through development of this technique. There are obvious benefits to operating a reconfigurable protocol stack in 21st Century networks due to increasing pressures on resources and the need to provide quality of service. A dynamic network architecture allows exactly

the right combination of protocols to be chosen for each application. However, reconfigurable protocol stacks remain to be deployed in networks today. An obvious concern which arises from the consideration of reconfigurable protocol stacks is the risk of increasing processing time when choosing the optimum stack configuration. There is also the risk that, in incorporating multiple choices into the stack, memory increases, and hence hardware costs, will be required.

There are several approaches to incorporating reconfigurability into the protocol stack. One approach is to empower the message with the intelligence to decide the path through the stack and the functions necessary in relation to the requirements of the packet [22] [23]. Another approach is to group the functions specific to an application at all layers [24] [25]. While there may be multiple functions within each layer, only one from each will be relevant to an application and the grouping will be determined in advance. The final approach investigated is to build a middleware layer into the stack, which makes provisions for allowing adaptability [26] [27].

The approaches presented are diverse and thorough, and yet many more exist in addition to those examined here [28] [29] [30]. However, each has certain features with specific application for various environments and applications. As with the multimedia protocols, the main criticism is that the majority of the proposed reconfigurable protocol stacks do not take environmental information into account when making protocol choices, but rely on the needs of the application. As transmissions depend heavily on the environmental constraints in the network, it is important that explicit network information is used in the decision-making process.

5 Research Proposal

Current transport layer protocols are incapable of achieving the stringent QoS requirements of real-time multimedia applications. They neither possess the capabilities to characterise applications nor adapt performance to maximise the possibility that QoS is achieved. Such functionalities, however, are thought paramount to the achievement of application QoS in tomorrow's networks.

The research proposal incorporates application and environmental information at the top of the stack to influence decisions made in the lower layers. In addition, the functionalities which are available in each layer will be increased. Currently, within the transport layer, either TCP [8] or the User Datagram Protocol (UDP) [31] will be available according to the nature of the application. Each protocol has well-defined and contrasting approaches to communication. However, network conditions can be extremely variable and dynamic. Therefore, my proposal incorporates a greater amount of variability into the transport layer, different protocols being more appropriate to use in different circumstances. The protocol stack will be evaluated on a hop-by-hop basis. Variability of protocol functions will be introduced in terms of connection orientation of the communication, flow control and the rate of flow control, error control, and the retransmission strategy. The proposed protocol stack is shown in Figure 1.

Environmental information is passed to the protocol stack via a connecting network diagnostic and management system. The diagnostic system will not be discussed in depth in this paper; this represents future work and may be documented at a later date. Several attributes are passed between the protocol stack and the diagnostic system. This is in keeping with Bashir et al's (2005) [32] opinion that network performance is typically measured using metrics for throughput, connectivity, end-to-end and round-trip packet delay, and packet loss.

Several of these parameters have been selected to combine environmental and application information. The subsequent result will be used to select the transport protocol. The formula is shown in Equation 1.

$$Result = \sqrt{\frac{\sqrt{BER}}{\left(\frac{\sqrt{U}}{D^{2e2}} * (D^b + D^t)\right) * ToS}} \tag{1}$$

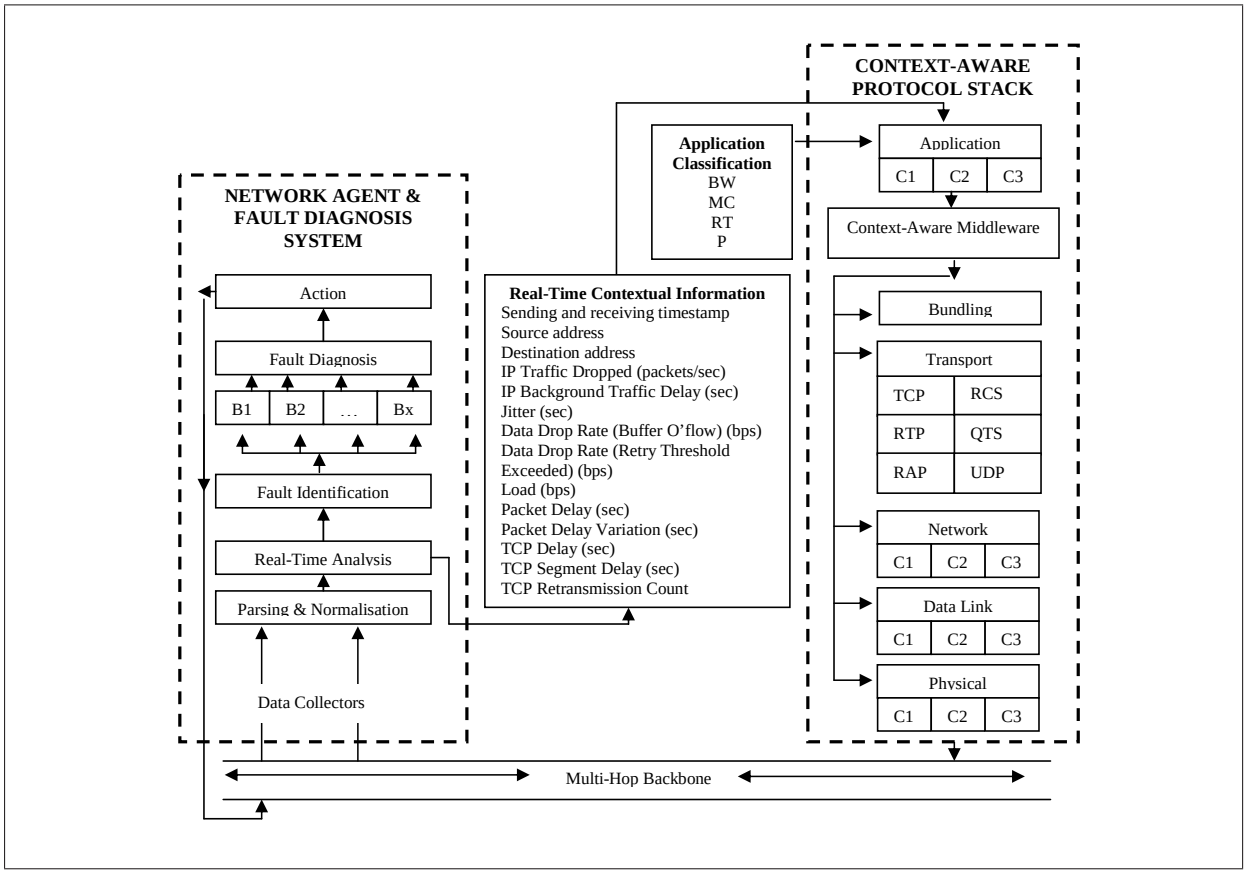

Figure 1: Proposed Protocol Stack and Network Management Function

Combination of Application and Environmental Information

Where:

U	Link Utilisation
D^{e2e}	End-to-End Delay
D^{b}	Data Drop (Buffer Overflow)
D^{t}	Data Drop (Retry Threshold Exceeded)
BER	Bit Error Rate
ToS	Type of Service

The Type of Service (ToS) attributes refers to the QoS required by an application. The scale being used is 0 - Best Effort Application, 3 - Excellent Effort, and 6 - Interactive Voice. The QoS therefore increases in parallel with the ToS value.

As an example of how this protocol stack will be used, it is the intention that where the link is under-performing (i.e. low link utilisation, high end-to-end delay, high number of data drops, and high BERs), the transport protocol deployed is one with a reduced amount of overhead. The rationale behind this approach is that, where the network is operating in a manner which is sub-optimal, a protocol with less control overhead should be used to maximise the opportunity that some of the data transmitted will be received (taking into account that IPTV is an application which can cope with some data loss). If a protocol with more stringent error-control requirements was used in such an environment, there is a greater opportunity that the data will not be received due to an inability to cope with data loss.

It should also be noted that, while it is shown in the stack that the complete protocols are deployed at each hop when the conditions are evaluated, it is the intention that the separate functionalities of each protocol can be called. For example, it may be decided that the four classes of service from BATS should

be deployed alongside the QTS error-control scheme (error-control only for loss-sensitive applications). It is the intention to call the current multimedia protocol functions to maximise their potential and the success of the transmission, given the application requirements and the environmental constraints. The calling of individual error, flow, and retransmission strategies will depend on individual formulaic conditions designed.

6 Implementation

Implementation of the research proposal has partially occurred. The functionality being documented in this paper is the integration of adaptability in terms of the connection-orientation of the communication. Within *Opnet* [33], this has involved integrating environmental information, which has not previously been provisioned for. The environmental information and the evaluation criteria discussed in Section 5 have been inserted into the application layer. Defined within the Function Block, the changes are subsequently called from the process model states when spawning the application profiles.

Dependencies between the layers have also been provisioned for. This has involved integrating the changes made in the application layer within the subsequent modules called. *Opnet* uses a global data structure from which it determines the transport protocol being used for any application. It is referred to several times in the initiation of a communication for the purpose of populating data structures with the transport protocol. One of the functions of this implementation was therefore to remove all reliances on the global transport protocol service, and to ensure that all references were instead made to the intelligently calculated protocol. Changes were required in the tpal layer and the process models generated by the spawning of the application process, the video_calling_manager and gna_profile_mgr models. After the tpal layer, the transport protocol module and the lower layers of the stack are called. As the changes are being made to the choice of transport protocol, all changes must therefore be made before this layer. Figure 2 shows the dependencies between the process modules, and the span of changes required to achieve implementation at the client.

The changes implemented in a top-down fashion between the application and tpal layers have ensured developments at the client. Developments must now be made in a bottom-up approach between the same layers to allow incorporation of the same changes at the server.

7 Conclusions and Future Work

The research proposal has been thoroughly investigated and it is believed that the proposed scheme can have a realistic existence in future networks. Reconfigurable protocol stacks have been widely investigated in the literature, but remain to be deployed. Given the dynamism of network conditions, it seems sensible to incorporate flexibility into the protocol stack. Conditions in the external environment are pivotal in enabling the transport protocol's operation, and hence the fulfilment of the application's requirements. Therefore, its incorporation into the decision-making process is thought fundamental to providing future service differentiation. It is the challenge to design one which is technically and commercially feasible.

This research has been conducted during a four-month Internship with Cisco Systems in Silicon Valley. The protocol stack developments discussed in this paper are also simultaneously being developed for a PhD research project. This Internship has allowed research to occur specifically on the transmission of multimedia, although the applicability of all application types to this proposal will be considered for the final project.

This period has seen the initiation of the task of delving into Opnet's code to modify how functions are performed at present. Future work will involve incorporating the other techniques with an adaptable status. These include flow control, error control, and the retransmission strategy.

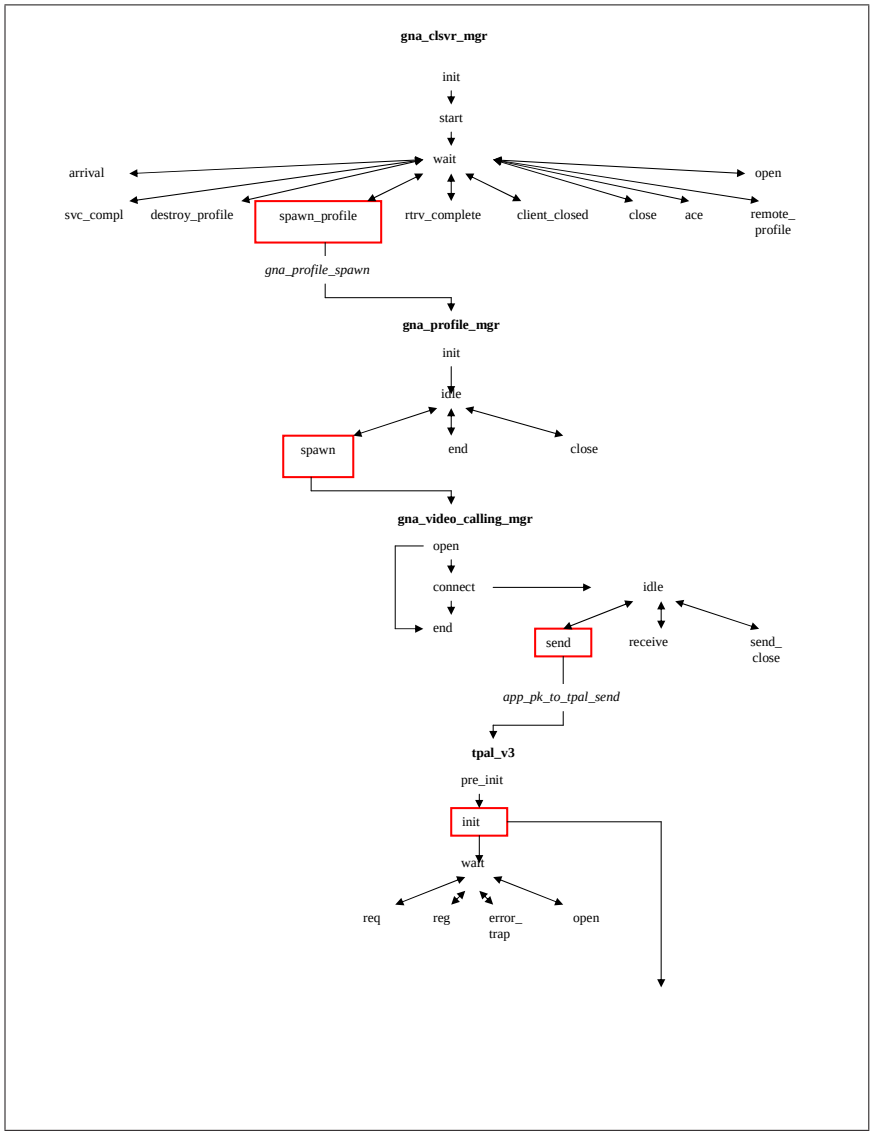

Figure 2: Data Flows from Application to Tpal Layers

References

[1] Multimedia Research Group, *"IP TV Global Forecast - 2006 - 2009: Semiannual IP TV Global Forecast"*, March 2006.

[2] Gartner Group, *"IPTV Prediction"*, Gartner Group Research Report, Winter 2005.

[3] Zadeh, A; Douglass, G, K; Dogra, R; *"Communications and High Tech: "Infinite Possibilities" Television?"*, Accenture, May 2006. Available at: http://www.accenture.com/Global/Research_and_Insights/Outlook/By_Issue/Y2006/ InfiniteTelevision.htm

[4] Shin, D, H; *"Potential User Factors Driving Adoption of IPTV. What are Customers Expecting from IPTV?"*, Technological Forecasting and Social Change, 2006.

[5] Harris, A; *"White Paper of Enabling IPTV: What Carriers Need to Know to Succeed"*, May 2005, IDC. Available at: http://www.emc.com/analyst/pdf/IDC_IPTV_WhitePaper_Jun_9_05.pdf

[6] Chan, S-P; Kok, C-W; Wong, A, K; *"Multimedia Streaming Gateway with Jitter Detection"*, IEEE Transactions on Multimedia, Volume 7, Number 3, June 2005, Pages 585 - 592.

[7] Rejaie, R; Handley, M; Estrin, D; *"RAP: An End-to-End Rate-Based Congestion Control Mechanism for RealTime Streams in the Internet"*, Proceedings of the Eighteenth Annual Joint Conference of the IEEE Computer and Communications Societies, Volume 3, 21 - 25 March 1999, Pages 1337 - 1345.

[8] Postel, J; *"Transmission Control Protocol"*, Request for Comments 793, September 1981.

[9] Yuang, M, C; Liu, J, C; Shay, C, L; *"BATS: A High-Performance Transport System for Broadband Applications"*, IEEE Proceedings of the 19th Conference on Local Computer Networks, 2 - 5 October 1994, Pages 448 - 455.

[10] Conti, M; Donatiello, L; Furini, M; *"Design and Analysis of RT-Ring: A Protocol for Supporting Real-Time Communications"*, IEEE Transactions on Industrial Electronics, Volume 49, Issue 6, December 2002, Pages 1214 - 1226.

[11] Yuang, M, C; Liu, J, C; *"QTS: A QoS-Guaranteed Transport System for Broadband Multimedia Communications"*, IEEE Transactions on Industrial Electronics, Volume 45, Number 1, February 1998, Pages 69 - 77.

[12] Schulzrinne, H; Casner, S; Frederick, R; Jacobson, V; *"RTP: A Transport Protocol for Real-Time Applications"*, Network Working Group, Request for Comments 3550, July 2003.

[13] International Organisation for Standardisation, *"Open Systems Interconnection - Basic Reference Model: The Basic Model"*, ISO/IEC 7498-1: 1994, Available at: http://isotec.iso.org/livelink/livelink/fetch/2000/2489/ lttf_Home/PubliclyAvailableStandards.htm

[14] Consultative Committee for Space Data Systems, *"CCSDS File Delivery Protocol (CFDP): Recommendation for Space Data System Standards"*, Blue Book, October 2002.

[15] Consultative Committee for Space Data Systems, Available at: www.ccsds.org

[16] Delay Tolerant Network Research Group. Available at: www.dtnrg.org

[17] Consultative Committee for Space Data Systems; *"Overview of Space Link Protocols"*, CCSDS 130.0-G-1, Green Book, June 2001.

[18] International Standards Organisation, Available at: www.iso.org

[19] Curran, K; Parr, G; *"The Use of Dynamically Reconfigurable Protocol Stacks for Streaming Multimedia to Mobile Devices"*, Proceedings of the 8th International Conference on Communication Systems, 25 - 28 November 2002, Volume 2, Pages 947 - 951.

[20] Johnny, T, F; *"Adaptive Protocol Suite for Next Generation Wireless Internet"*, Proceedings of the IEEE 2005 International Conference on Personal Wireless Communications, 23 - 25 January 2005, Pages 509 - 513.

[21] Akyildiz, I; Altunbasak, Y; Fekri, F; Sivakumar, R; *"AdaptNet: An Adaptive Protocol Suite for the Next-Generation Wireless Internet"*, IEEE Communications Magazine, March 2004, Pages 128 - 136.

[22] O'Malley, S, W; Paterson, L, L; *"A Dynamic Network Architecture"*, ACM Transactions on Computer Systems, Volume 10, Number 2, May 1992, Pages 110 - 143.

[23] Schöler, T; Müller-Schloer, C; *"Design, Implementation and Validation of a Generic and Reconfigurable Protocol Stack Framework for Mobile Terminals"*, Proceedings of the IEEE 24th International Conference on Distributed Computing Systems Workshops, 2004.

[24] Haas, Z; *"A Protocol Structure for High-Speed Communication over Broadband ISDN"*, IEEE Network Magazine, January 1991, Pages 64 - 70.

[25] Zitterbart, M; Stiller, B; Tantawy, A, N; *"A Model for Flexible High-Performance Communication Subsystems"*, IEEE Journal on Selected Areas in Communications, Volume 11, Number 4, May 1993, Pages 507 - 518.

[26] Curran, K; Parr, G; *"The Use of Dynamically Reconfigurable Protocol Stacks for Streaming Multimedia to Mobile Devices"*, Proceedings of the 8th International Conference on Communication Systems, 25 - 28 November 2002, Volume 2, Pages 947 - 951.

[27] Zhang, C, H; Chin, T, K; Koh, K, Y; Ong, G, M; Suthon, S; Peng, C, H; Pung, H, K; *"Octopus: An Adaptive Group Communication Environment for Multimedia Application"*, The IEEE 10th International Conference on Networks, 27 - 30 August 2002, Pages 145 - 150.

[28] Akyildiz, I; Altunbasak, Y; Fekri, F; Sivakumar, R; *"AdaptNet: An Adaptive Protocol Suite for the Next-Generation Wireless Internet"*, IEEE Communications Magazine, March 2004, Pages 128 - 136.

[29] An, L; Pung, H, K; Zhou, L; *"Design and Implementation of a Dynamic Protocol Framework"*, Computer Communications 29, 2006, Pages 1309 - 1315.

[30] Guan, S-U; Lim, S-S, *"Modeling Adaptable Multimedia and Self-Modifying Protocol Exceution"*, Future Generation Computer Systems 20, 2004, Pages 123 - 143.

[31] Postel, J, *"User Datagram Protocol"*, Request for Comments 768, August 1980.

[32] Bashir, O; Parish, D; Sandford, M; Phillips, I; *"Optimising Data Processing in Network Performance Monitoring Systems"*, Proceedings of the IEE Communications, Volume 152, Issue 5, 7 October 2005, Pages 633 - 642.

[33] Opnet, Available at: www.opnet.com

Cathryn Peoples, Gerard Parr, Sally McClean, Michaela Black
University of Ulster
School of Computing and Information Engineering
Coleraine, Northern Ireland BT52 1SA
E-mail: {si.mcclean,gp.parr,mm.blackg}@ulster.ac.uk

Petre Dini
Cisco
170 West Tasman Drive San Jose, CA 95134 USA
E-mail: pdini@cisco.com

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Multiobjective Optimization Scheduling Problems by Pareto-optimality in Agro-alimentary Workshop

Fatma Tangour, Ihsen Saad

Abstract: This paper deals with the multiobjective optimization problem of an agro-alimentary production workshop. Three criteria are considered in addition to this initial cost of production: the cost of the out-of-date products, the cost of the distribution discount and the makespan, and a new coding is proposed for this type of workshop. The adopted approach consists in generating optimal solutions diversified in the search space of solutions, and to help the decision maker when it cannot give a particular preference to one of the objective functions to make the good decision with respect to the quoted criteria.

Keywords: Agro-alimentary workshop, scheduling problems, genetic algorithms, Pareto-optimality, multiobjective optimization, production cost, makespan.

1 Introduction

Multi-objective optimization aims to optimize several components of an objective functions vector. Contrary to mono-objective, the multi-objective problem usually does not have a solution optimizing the whole concerned criteria, but a set of solutions, known as the set of the Pareto-optimal solutions. Any solution of this unit is optimal in the sense that no improvement can be made on a component without degradation of at least another component of the vector [15]. Given that a solution chosen by a decision maker can not be acceptable by another, it proves to be useful to envisage several alternatives to the choice of a Pareto optimal solution [18]. In this article, the scheduling problems in the agro-alimentary production workshops are dealt [6]. The principal objective is to search a realizable scheduling minimizing the makespan, the cost of the out-of-date products and the cost of the distribution discount. The transformation methods of the multi-objective problems into mono-objective problems are applied [2]. This article is organized as follows. The one machine scheduling problem is formulated in section 2; the resolution approach suggested with this problem is described in section 3. The effectiveness of this approach is tested for some examples in section 4.

2 Problem formulation

The problem is to build a multi-objective one machine scheduling problem adapted to agro-alimentary industries. Among the constraints and the criteria specific to agro-food industry, the out-of-date of the products and the discount of distribution can be distinguished. The objective is then to select among the cases of realisable scheduling the one which presents the best reducing compromise between the various criteria [7].

The goal of this study is, then, to minimise these criteria such as:

- C_1 : the cost of the out-of-date products,
- C_2 : the cost of the distribution discount,
- C_3 : the makespan.

The basic production cost on the one machine problem is supposed independent from the scheduling.
The data of the considered case are as follows:
We have a set n of operations, each operation is characterised by its earliest starting time, its effective starting time, its processing time and its effective completion time.

Notations :

t_i : effective starting time of operation O_i,
r_i : earliest starting time of the operation O_i,
γ_i : effective completion time of the operation O_i,
p_i : processing time of the operation O_i,
P_i : finished product of the operation O_i,
c_{ik} : k^{th} component of the components set of the operation O_i,
v_{ik} : validity limit date of the component c_{ik},
C_{P_i} : completion time of product P_i,
$d_{P_i}^{liv}$: delivery date of the product P_i,
Dv_{P_i} : lifespan of the product P_i,
Dr_{P_i} : return delay of the product P_i,
P_{ik}^{rev} : cost price of the component of the c_{ik} product P_i,
$P_{P_i}^{ven}$: unit selling price of the product P_i
$C_{P_i}^{stk}$: cost of storage per unit of time of a unit of the product P_i.

2.1 Criteria formulations

Three criteria are considered. The two first constitute criteria specific to the agro-alimentary production workshops [16]. The last criterion is traditional and used for the optimization of the scheduling problems of a traditional production workshop.
The considered objectives relate to minimization:

- C_1: the cost of the out-of-date products

$$C_1 = \sum_i \sum_k P_{ik}^{rev} \left(\frac{\max(0, t_i - v_{ik})}{(t_i - v_{ik})} \right) \tag{1}$$

- C_2: the cost of the distribution discount

$$C_2 = \sum_i \max\left(0, d_{P_i}^{liv} - C_{P_i}\right) \times \left(\frac{P_{P_i}^{ven}}{Dv_{P_i} - Dr_{P_i}} + C_{P_i}^{stk} \right) \tag{2}$$

- C_3: the makespan

$$C_3 = \sum_i (t_i + p_i) \tag{3}$$

2.2 Lower bound Formulations

Proposition 1. *$C_i \geq 0$, $\forall i \in \{1,2\}$ and $C_i^b = 0$; where C_i^b represents the lower bound of the criteria C_i.*

Proposition 2. *The lower bound of the makespan, C_3^b is defined as follows:*

$$C_3^b = \sum_i \min(r_i + p_i) \tag{4}$$

Proof. When: $C_3 = \max_{1 \leq i \leq n} \gamma_i$, $t_i \geq r_i$ and then

$$C_3^b = \min \left(\sum_i (t_i + p_i) \right) \tag{5}$$

$$C_3^b = \sum_i \min (r_i + p_i) \tag{6}$$

□

3 Genetic Algorithms application for the scheduling problems

3.1 principle

Various approaches have been proposed to solve scheduling optimization problems, among them the Genetic Algorithms (GAs) approach can be distinguish. This approach was largely adopted these last years [11], [14]. The use of GAs in many fields proved reliable in particular in combinatorial problems such as the scheduling problems [3], [4], [12]. Other hybrid algorithms have also been proposed [1] [8].The main difficulty in the resolution of these problems types results in their algorithmic representation form, which constitutes the most significant point in genetic search. Several representation approaches and various standard AGs operators were proposed, to solve these problems. Among them, the representation based on the priority rules [5]. The principle of a simple Genetic Algorithm is as follows, figure 1.

3.2 Proposed Genetic Algorithm Coding

Proposed coding in the application case is: Ordered Operations Coding Lists "OOCL", table 1. Inspired from the CLO (Operation List Coding) coding [9] and the CPM (Parallel Machines coding) coding [10], it consists in proposing ordered lists for the products line. The proposed coding defined the ordered, the starting time and the completion time of the operations. These dates are calculated and updated by the "dates calculation algorithm", table 2.

Table 1: OOCL Coding

1	2	3	4
O_2, t_2, γ_2	O_1, t_1, γ_1	O_4, t_4, γ_4	....

Table 2: dates calculation algorithm

t_i	: effective starting time of operation O_i, $t_i = \max(r_i, \gamma_j)$
γ_i	: completion time of the operationO_i, $\gamma_i = \max(r_i, \gamma_j) + p_i$
where γ_j represents the completion time of the operation O_j that preceded O_i	

The operators used for this coding are: mutation, crossover at a point and crossover at two points. The mutation operator chooses two points of the same individual (list), to generate another individual, table

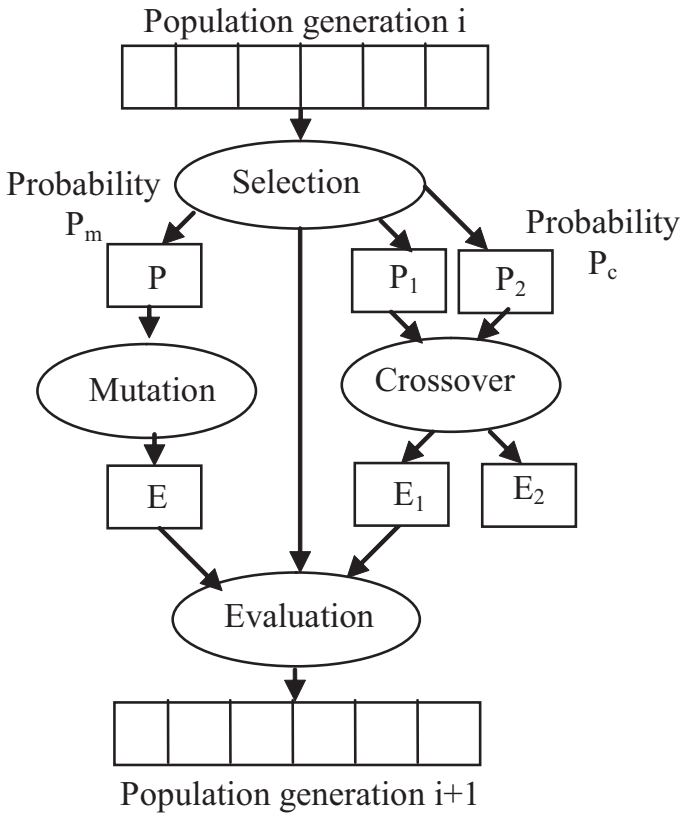

Figure 1: Genetic Algorithm principle

3. The crossover at a point operator chooses, two individuals' parents to generate two other individuals' children starting from only one point, table 4. And the two points crossover operator chooses, two individuals to generate two other individuals starting from two points, table 5.

Table 3: Mutation algorithm

Beginning

1. Choose two positions i and j of the same individual, for each position correspond an operation O_i and O_j,
2. Permute between the operations O_i and O_j to obtain the child,
3. Update the child,
4. Calculate C_1 ,C_2 ,C_3 of the new individual according to the "dates calculation algorithm",

End

3.3 Multi-objective evaluation approach

Generally, the considered criteria present nonlinear and complexes relations and do not have the same importance from the point of view of decision maker. Thus, much of considerations can be retained to take account of all these difficulties. With this intention, a fuzzy method evaluation is proposed. This method is based on the steps which follow [13]:

For each objective function a lower bound is calculated as follow:

$$C_i(x) \geq C_i^b \ \ \forall x \in S, \quad 1 \leq i \leq n_c \tag{7}$$

where S represents the space of realisable solutions and n_c the number of objective functions.

The fuzzification is applied by the functions described, figure 2.

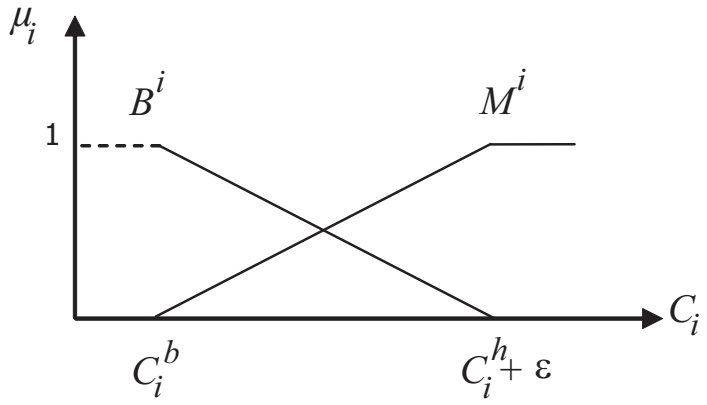

Figure 2: Fuzzy application in the resolution of the scale problem

For each realizable solution x, a vector $C(x)$ is associated, $C(x) \in \left[C_1^b, +\infty\right] \times ... \times \left[C_{n_c}^b, +\infty\right]$, then $C(x) = (C_1(x), ..., C_{n_c}(x))^T$; for each vector $C(x)$, a fuzzification of their components is proposed and

Table 4: Crossover I algorithm

Beginning

1. Choose two individuals P_1 and P_2, and a crossover point
2. Go to all the operations

   While $i < n$ *do*

   - *If* $j < i$ *then*
     - copy the operations of the P_1 in the child1
     - copy the operations of the P_2 in the child2
   - *Else* copy from P_2 (respectively P_1) with the same position, the missing operations in the child1(respectively child2)
   - *End If*

   End while
3. Finish the construction of the child1 (respectively of the child2) with the missing operations (by respecting the order)
4. Update the child1 and the child2
5. Calculate C_1, C_2, C_3 of the two new individuals according to the "dates calculation algorithm"

End

Table 5: Crossover II algorithm

Beginning

1. Choose two individuals P_1 and P_2 and two crossover points i and k
2. Go to all the operations

   While $i < n$ *do*

   - Copy the operations of the P_1, which precede the first crossover point and which follows the second crossover point, in the child1
   - Copy the operations of the P_2, which precede the first crossover point and which follows the second crossover point , in the child2
   - Copy, with the same position, the missing operations of the P_2 in the child1
   - Copy, with the same position, the missing operations of the P_1 in the child2

   End while
3. Finish the construction of the child1 (respectively of the child2) with the missing operations (by respecting the order)
4. Update the child1 and the child2
5. Calculate C_1, C_2, C_3 of the two new individuals according to the "dates calculation algorithm"

End

considered as two sub-sets B^i and M^i, figure 2.

$$\text{if } C_i(x) \in \left[C_i^b,\, C_i^h + \varepsilon\right] \text{ then } \mu_i^B(C_i(x)) = \frac{C_i^h - C_i(x) + \varepsilon}{C_i^h - C_i^b + \varepsilon}, \text{ else } \mu_i^B(C_i(x)) = 0 \tag{8}$$

when C_i^hrepresents the maximum value of the solution given by a considered heuristics according to the i^{th} objective function.

$\mu_i^B(C_i(x))$ is considered as the fuzzy measurement of $C_i(x)$ in the sub-set B^i.

Then, the quality of each solution is characterized by the vector $C_B(x)$ where all the components are homogeneous since they belong to the same interval and are all without dimension.

$$\begin{aligned} &C_B(x) = (a_1, ..., a_{n_c})^T \\ &a_i = \mu_i^B(C_i(x)), \quad \forall i = 1, 2, ..., n_c \end{aligned} \tag{9}$$

For the multi-objective evaluation, the objective function $C_g(x)$ is reduced to the minimization of the balanced sum of the criteria relating to the use of the aggregation operator OWA [17].

$$C_g(x) = \sum_{i=1}^{n_c} w_i a_i \tag{10}$$

A set of Pareto-optimal solutions is built without according privilege to a particular search direction, to help the decision maker when it cannot clearly give a particular preference to an objective function. This approach is based on an algorithm in which, the objective function $C_g(.)$, defined at the relation (10), is used for the evaluation of solutions. Weightings w_i $(1 \leq i \leq n_c)$ are calculated by using a fuzzy rule. The idea is to measure the average quality of the solutions according to each criterion for each iteration and to calculate the various weights according to the degree of this quality.

The goal is to study the profits and the possible improvements of the solutions by giving the priority to the optimization of the objective functions whose average values is far from the lower bound. This approach is called aggregative approach with dynamic search direction. Let $\vec{C_i^k}$ be the solutions average of the i^{th} objective function found at k^{th} iteration.

$$\vec{C_i^k} = \frac{\sum\limits_{x \in P_k} C_i^k(x)}{card(P_k)} \tag{11}$$

where P_k represents the solutions population at this iteration.

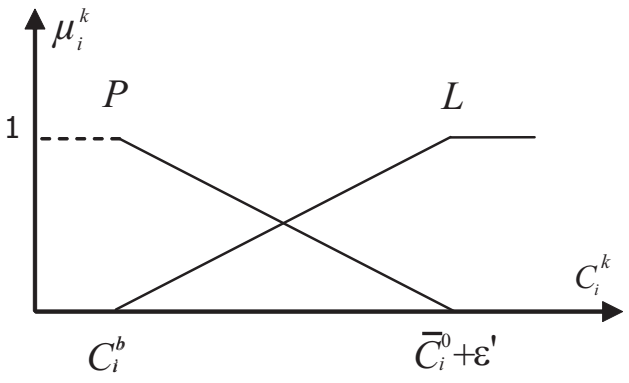

Figure 3: Criteria membership function

For each vector $C(x)$, a fuzzification is applied to its components $C_i(x)$ according to their positions in the interval $\left[C_i^b,\, \vec{C_i^0} + \varepsilon'\right]$; where ε' is a little positive value introduced to avoid the division by zero, if $\vec{C_i^0} = C_i^b$ then $\varepsilon' = 0.1C_i^b$, else $\varepsilon' = 0$.

The evaluation of the solutions quality is done by using the membership functions defined in figure 3, relating to the two fuzzy subsets, "P" and "L" of the lower bound.

The membership functions can thus be formulated as follows:

$$\text{if } \bar{C}_i^k \in \left[C_i^b,\, \bar{C}_i^0 + \varepsilon'\right] \text{ then } \mu_{ik}^L\left(\bar{C}_i^k\right) = \frac{\bar{C}_i^k - C_i^b}{\bar{C}_i^0 - C_i^b + \varepsilon'} \text{ else } \mu_{ik}^L\left(\bar{C}_i^k\right) = 1 \tag{12}$$

The calculation of various weightings is carried out by using the two following fuzzy rules:

- If (C_i^k is "P" fromC_i^b) then (w_i^{k+1} decrease)
- If (C_i^k is "L" fromC_i^b) then (w_i^{k+1} increase)

Which lead to the following expression:

$$w_i^k = \frac{\mu_{ik}^L\left(\bar{C}_i^k\right)}{\sum_{j=1}^{n_c} \mu_{jk}^L\left(\bar{C}_j^k\right)},\ \forall i\, \forall k \tag{13}$$

where $1 \leq i \leq n_c$ and $2 \leq k \leq Q$, with Q the total number of iterations and "L" the index relating to the fuzzy subset.

w_i^1 corresponds at the first iteration defined as follow:

$$w_i^1 = \frac{1}{n_c},\ \forall i = 1, ..., n_c \tag{14}$$

The various weighting vectors $(W^1, W^2, ..., W^Q)$ are gradually calculated from the k^{th} generation P_k at the generation P_{k+1}, according to the distance between the lower bounds and the average of the k^{th} generation individuals, represented by a black circle in the figure 4.

The objective is to improve of the solutions by giving the priority to the objective functions optimization whose average of the values is far from the lower bound. Indeed, by using a fuzzy rule, it is possible to control the search direction in order to build a final set with solutions approaching as much as possible the optimal values.

This method, can be used when the decision maker cannot give a particular preference to an objective function, it also makes it possible to generate weights of the different criteria from an iteration to another in a dynamic way according to the average of the solutions.

4 Simulation

To illustrate the effectiveness and performance of the proposed approach, six representative examples based on practical data have been selected to compute. These examples deal with 5 to 10 operations. The proposed approach is applied to them to optimize three criteria, represented in eqs. (1-3).

For example, the data relating to the example which treats 10 operations and which treats 5 operations is represented respectively in table 6 and table 7.

By application of the proposed approach, the following experimental results are obtained, table 8.

The different results show that the solutions obtained are generally acceptable and satisfactory. The values of the different objective functions show the efficiency of the suggested approach, table 8.

Moreover, the proposed method enables us to obtain good results in a polynomial computation time. In fact, the various values of the criteria given by the multiobjective optimization method by Pareto-optimality show its effectiveness, table 8. The values of the criteria for the Pareto border are in the neighbourhood of to the lower bounds. Indeed, such an approach makes it possible to generate Pareto-optimal solutions of good quality.

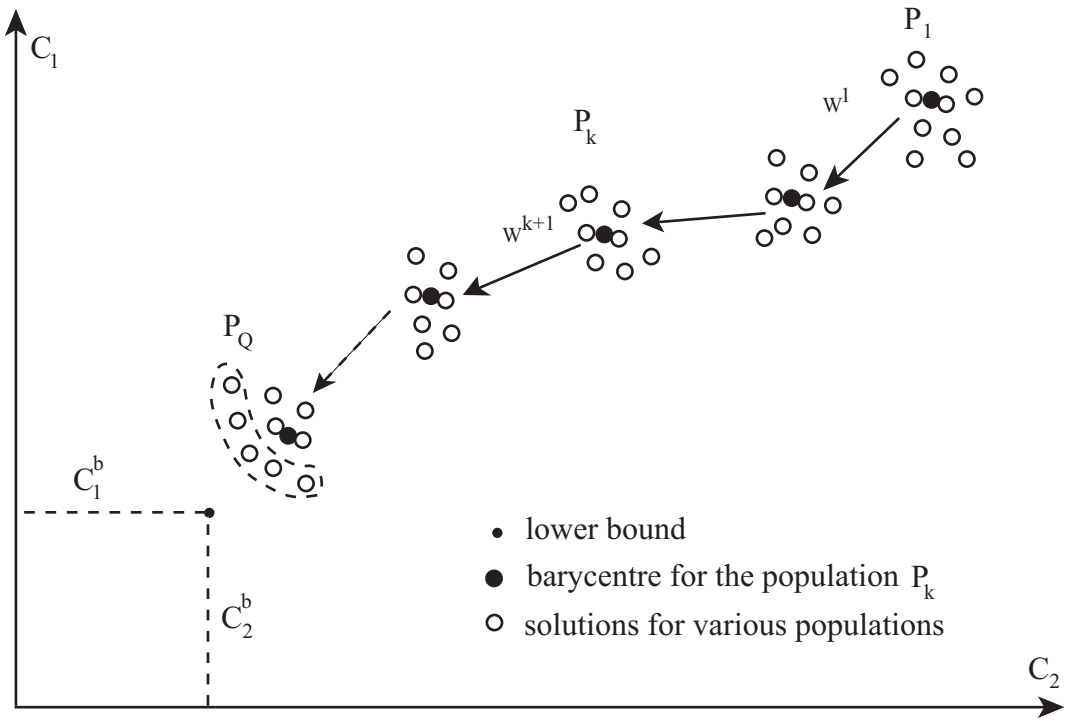

Figure 4: Search direction

Table 6: data relating to 10 operations

	O_1	O_2	O_3	O_4	O_5	O_6	O_7	O_8	O_9	O_{10}
r_k	0	1	2	3	4	1	3	2	1	3
p_k	1	2	4	2	1	2	1	3	2	4
v_{i1}	13	14	13	13	12	7	7	13	9	9
v_{i2}	15	14	5	14	13	15	15	16	15	15
v_{i3}	-	12	13	12	11	14	14	12	14	14
P_{i1}^{rev}	2	3	4	3	2	1	1	2	2	2
P_{i2}^{rev}	1	2	2	4	3	2	2	1	4	1
P_{i3}^{rev}	-	4	3	2	2	1	3	2	3	3
Dv_{P_k}	35	32	35	33	35	36	31	34	36	31
Dr_{P_k}	14	10	9	11	8	12	7	9	11	10
$d_{P_k}^{liv}$	21	22	25	22	21	20	21	24	26	22
$C_{P_k}^{stk}$	3	2	2	5	2	3	4	3	1	2
$P_{P_k}^{ven}$	4	6	6	8	7	5	6	8	3	5

Table 7: data relating to 5 operations

	O_1	O_2	O_3	O_4	O_5
r_k	2	3	1	4	3
p_k	1	2	4	2	3
v_{i1}	3	3	4	6	5
v_{i2}	4	1	2	4	3
v_{i3}	2	-	3	-	4
P_{i1}^{rev}	1	2	1	2	4
P_{i2}^{rev}	3	1	2	4	2
P_{i3}^{rev}	4	-	3	-	1
Dv_{P_k}	14	16	10	11	14
Dr_{P_k}	5	6	4	7	5
$d_{P_k}^{liv}$	10	13	14	16	12
$C_{P_k}^{stk}$	1	2	3	4	5
$P_{P_k}^{ven}$	8	3	8	5	4

Table 8: experimental results

n	Scheduling	C_1	C_2	C_3	$C_g(.)$
10	$O_1O_3O_5O_9O_4O_2O_7O_6O_8O_{10}$	14	4	24	0,915
9	$O_1O_2O_3O_4O_5O_7O_6O_8O_9$	9	4	20	0,95
8	$O_1O_7O_5O_2O_3O_8O_4O_6$	14	1	18	0,963
7	$O_1O_3O_6O_7O_4O_2O_5$	12	9	17	0,752
6	$O_1O_4O_3O_5O_2O_6$	4	10	14	0,977
5	$O_1O_4O_5O_3O_2$	12	10	14	0,53

5 Conclusion

A new approach based on the hybridization with the Pareto-optimality for solving multiobjective problems in agro-alimentary workshop, is presented. The approach developed in this work provides the possibility to determine an optimal scheduling among several realizable ones; this optimal solution generates the minimization of objective function (10). Besides, the proposed approach uses Pareto to estimate and to classify obtained decisions. Indeed, we can avoid the preemption of certain components, the cost of the out-of-date products, the cost of the distribution discount and the completion time(makespan).

The proposed hybrid approach presented in this paper can be considered as effective mechanisms from the computation complexity.

References

[1] S. Cavalieri, P. Gaiardelli, Hybrid genetic algorithms for a multiple-objective scheduling problem, *Journal of Intelligent Manufacturing*, Vol.9, pp.361-367, 1998.

[2] Y. Collette, P. Siarry, Optimisation multiobjectif, *Editions Eyrolles*, Paris, 2002.

[3] L. Davis, Job shop scheduling with genetic algorithm, *Proceedings of the first International Conference on Genetic Algorithms*, Lawrence Erlbaum Associates, pp.136-140, 1985.

[4] F. Della Croce, R. Tadei, G. Volta, A genetic algorithm for the job shop problem, *Computer and Operations Research*, Vol. 22, No 1, pp. 15-24, 1995.

[5] U. Dorndorf, E. Pesch, Evolution based learning in a job shop environment, *Computers and Operations Research*, Vol. 22, pp.25-40, 1995.

[6] E. Gargouri, S. Hammadi, A distributed scheduling for agro-food manufacturing problems, *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, Vol. 33, No 2, 2003.

[7] E. Gargouri, S. Hammadi, P.Borne, New constraints of agro-food industry scheduling problem, *Acte de IFDICON'2001, Europeen Workshop on Intelligent Forecasting, Diagnostic and Control*, 24-28 juin, pp. 73-80, Santorin, 2001.

[8] A. K. Jain, H. A. El Maraghy, Single process plan scheduling with genetic algorithm, *Production Planning and Control*, Vol.8, No 4, pp.363-376, 1997.

[9] I. Kacem, S. Hammadi, P. Borne, Pareto-optimality approach for flexible job-shop scheduling problems: Hybridization of evolutionary algorithms and fuzzy logic, *Math. and Computers in Sim.*, 60, pp. 245-276, 2002.

[10] K. Mesghouni, Application des algorithmes évolutionnistes dans les problèmes d'optimisation en ordonnancement de la production , PhD Thesis, *Université des Sciences et Technologiques de Lille*, Lille, 1999.

[11] M. Mori, C. Tseng, Genetic algorithms for multimode resource constrained project scheduling problem, *European Journal of Operational Research*, Vol.100, No 1, pp.134-141, 1997.

[12] R. Nakano, T. Yamada, Conventional genetic algorithm for job shop problems, *Proceedings of the 4th International Conference on Genetic Algorithms*, University of California, pp. 474 -479, 1991.

[13] I. Saad, M. Benrejeb, Optimisation multicritère par Pareto-optimale des problèmes d'ordonnancement en tenant compte du coût de production, *Revue Sciences et Technologies de l'Automatique, e-STA*, Vol. 3, No. 1, 2006.

[14] M. Sakawa, Genetic algorithms and fuzzy multiobjective optimization, *Dordrecht: Kluwer Academic*.

[15] E. G. Talbi, Métaheuristiques pour l'optimisation combinatoire multiobjectif, *Tutorial, Journées Evolutionnaires Trimestrielles*, Paris, 1999.

[16] F. Tangour, S. Hammadi, P. Borne, M. Benrejeb, Ordonnancement dynamique dans un atelier de production agroalimentaire, *Séminaire d'Automatique-Industrie, SAI'06*, Matmata, 2006.

[17] R. R. Yager, On weighted median aggregation operators in multicriteria decision making, *IEEE Trans. on Systems, Man and Cybernetics*, 18, pp. 183-190, 1988.

[18] E. Zitzler, L. Thiele, Multi-objective Evolutionary Algorithms: A Comparative Case Study and the Strength Pareto Approach. *IEEE Transactions on Evolutionary Computation*, Vol.3, No 4, pp. 257-271, November, 1999.

Fatma TANGOUR[1,2], Ihsen SAAD[1,2]

[1]Ecole Nationale d'Ingénieurs de Tunis
Unité de recherche LARA-Automatique
BP 37, Le Belvédère, 1002 Tunis, Tunisie

[2]Ecole Centrale de Lille, Cité scientifique
Laboratoire d'Automatique, Genie Informatique et Signal
BP 48, 59651 Villeneuve d'Ascq Cedex, France

E-mail: {fatma.tangour, ihsen.saad}@enit.rnu.tn

Editor's note about the authors:

Fatma TANGOUR was born in 1969 in Nabeul, Tunisia. She graduated from "Ecole Normale Superieure de l'Enseignement Technique" and obtain the Master of automatic and signal treatment in 2004 at the "Ecole Nationale d'Ingénieur de Tunis". She is currently preparing the Ph.D. degree in automatic and computer science within the framework of LAGIS-EC-Lille and LARA-ENIT cooperation. Her research interests are in the area of optimization methods for discrete events systems, computer science and operational research.

Ihsen SAAD was born in Monastir, Tunisia, in 1977. He received the Engineer Diploma degree in electrical automatic control engineering from the "Ecole Nationale d'Ingénieur de Gabès", Tunisia, in 2002. He obtain the Master of automatic and signal treatment in 2004 at the "Ecole Nationale d'Ingénieur de Tunis". He is currently preparing the Ph.D. degree in automatic and computer science within the framework of LAGIS-EC-Lille and LARA-ENIT cooperation. His research is related to the evolutionary optimization methods for discrete events systems, computer science and operational research.

IFAC - LSS 2007
11th IFAC/IFORS/IMACS/IFIP
Symposium on Large Scale Systems Theory and Applications

Symposium on Large Scale Systems Theory and Applications to be held in Gdansk, Poland, 23-25 July 2007 under the auspices of IFAC, the International Federation of Automatic Control., http://www.ely.pg.gda.pl/lss2007.

The symposium covers all major aspect concerning large scale complex systems. It treats both theory and specific applications in large scale complex systems. The aim of the meeting is to promote the research activities and the cooperation between researchers in these areas.

Scope of the symposium:

The 11th IFAC/IFORS/IMACS/IFIP Symposium on Large Scale Systems: Theory and Applications is a core triennial event of IFAC Technical Committee on Large Scale Complex Systems. It has been held in Touoluse (1980), Warsaw (1983), Zurich (1986), Berlin (1989), Beijing (1992), London (1995), Patras (1998), Bucharest (2001) and Osaka (2004).

Traditionally, the LSS Symposium has considered generic issues arising in large scale complex systems and also has addressed relevant application areas. Advances in computer and network technologies on one hand and natural development of civilization on the other hand have produced new and highly complex large scale systems. Also, solving problems related to existing large scale systems that have not been solved yet have now become possible.

The meeting is to discuss new developments in methodologies and techniques useful in handling complexity in the modelling, decision support, control and design of large scale complex system. The methodologies and tools for the complexity analysis are to be among the key issues to be addressed by the Symposium. As in the past, a number of application areas will be addressed. Special attention will be paid to environmental systems in order to respond to increasing demand on suitable methodologies and tools.

The Mini-Symposium on Technology, Automation and Automatic Control of Wastewater and Drinking Water Systems will be organised by Working Group on Monitoring and Control of Large Scale Water and Wastewater Systems as an integral component of the Symposium.

It has now become clear that successful problem solving in large scale complex systems requires interdisciplinary teams to be involved. It has been recently recognised that proper and broad education of system thinking is a key factor in preparing infrastructure that is needed to set up such teams. Hence, the topic of system thinking education for problem solving in large scale complex systems will be addressed by a technical session. Finally, the business systems are to be stronger addressed than it was done in past.

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Coalition Formation for Cooperative Information Agent-Based Systems

Nacer eddine Zarour, Sabrina Bouzidi

Abstract: The communication technology evolution led to an increase of the carried out services' and tasks' number. The aim of actual research in the cooperation and particularly the negotiation between agents is to reach a coherent global state of the multiagent system by favoring agents' synergy. In this paper, we propose a coalition formation-based negotiation model for the task allocation in the cooperative information agent-based systems. In this model, the agent that activates a negotiation seeks partners for achieving a complex task. The way that the partners take part in a coalition is done one by one according to the choice of all the coalition members. This choice is based on a multicriterion analysis. Some obtained experimental results show the suggested model performances.
Keywords: Negotiation, coalition formation, cooperative information systems, multiagent systems, task allocation.

1 Introduction

In an open environment as Cooperative Information Systems (CISs), which gathers distributed; heterogeneous; and autonomous Information Systems (ISs), the cooperation requires the intervention of a negotiation process in order to identify and structure the various problems, to propose and defend the solutions, to re-examine the intentions in a conflict, and finally to confirm the commitments [1]. In our context, each IS is modelled by an autonomous, rational, and egoistic agent.

Several negotiation models were developed like *Market mechanisms* [2], *Contract Net Protocol* [3], *Social Laws* [4], *MultiAgent Planification* [5], and *Organizational structures (coalitions, teams, congregations, etc.)* [6]. The coalition formation is a negotiation technique which is particularly preferred for solving the conflicts between agents whose behavior is economic and thus rational. A coalition is a short-term organization based on specific and contextual commitments of involving agents. This allows agents to profit from their respective competencies. To solve the task allocation problem, several coalition formation-based models were suggested [7] [8] [3]. However, these models are not adapted to the context of CISs because they do not define relations of partnership between agents, but rather relations of subcontracting. Generally in these models, the agent that activates a negotiation process will only decides to structure the coalition. It selects its partners separately according to its own desires. Consequently, the agents' autonomy is not respected.

The objective of this work is to propose a coalition formation-based model for the task allocation in CISs. The proposed model, named CFoTACIS[1] , is inspired from the reality of the cooperation between entreprises. It respects the agents' autonomy by allowing them to take part in the coalition formation process. It is recursive and includes four phases, the initialization, the negotiation, the evaluation, and the finalization.

The rest of the paper is organized as follows. In the following section, we present some related work to the coalition formation. In section 3, we develop the suggested negotiation model. Section 4 enumerates the proposed model properties. Some experimental results are presented in section 5. Section 6 summarizes the contributions of this paper and the research perspectives.

[1]Coalition Formation for Task Allocation in Cooperative Information Systems.

Selected paper from ICCCC 2006

2 Related work

According to the literature, we consider two approaches for studying the coalition formation process, the macroscopic approach and the microscopic one. *The macroscopic approach*, which is based on the game theory, considers the coalition as the basic unit [9]. *The microscopic approach* considers agents as the basic unit where several models were proposed and applied in many fields, especially the e-business [10] and the task allocation [7] [8] [3].

We focuss our discussion on the models based on the second approach which deal with the task allocation problem. In [7], the authors proposed a model where agents exchange their preferences w.r.t. the possible solutions. Although, forcing agents to form alliances ensures the termination of the negotiation process, but the model does not respect agents' freedom since it imposes a solution which may not satisfy all agents.

In [8], the authors propose a model where the agent that activates the negotiation process first filters agents of its environment. It uses a multicriterion analysis to find agents that best satisfy its requirements. Then, it starts an argumentative negotiation with the candidates, which are classified according to its preferences. This approach does not ensure the reach of a consensus but limiting the negotiation time seems to be a reasonable strategy.

Two models are proposed in [3]. The first one is dedicated to the competitive agents. The agent selection is based on a preference model, which is built using several criteria. The major inconvenient of this model is that the representing agent of the coalition has a kind of authority on the coalition members. In the second model, agents cooperate in an altruistic way. The model ensures the reach of a consensus and has some advantages like the integration of the new partners one by one in the coalition. However, the altruistic strategy of agents does not require the gradual integration of agents in the coalition. This approach seems to be interesting in the case of egoistic agents. In [10], the authors proposed a formalization of the trust criteria which an agent grants to the other ones of the environment. This trust modeling ensures the stability in the coalition formation due to its reliability. However, the authors do not specify how to find the value of the current evaluation of trust. In order to response at this question in our proposal, we will deduce the trust from some criteria.

3 CFoTACIS: A coalition formation-based negotiation model in CISs

Before describing the suggested model, let us admit the following assumption: an agent which wants to integrate the CIS must update the portal of this CIS [4]. It must specify its localization, its know-how, the information about its branch of industry, its competencies, its capital, etc.

CFoTACIS is recursive and includes four phases, the initialization, the negotiation, the evaluation, and the finalization. In the beginning of the negotiation process, the manager which is the first coalition member, follows only the model phases. After that, when new partners join the coalition and become members, all the members try to find the next partner. The negotiation process iters until the coalition size will be reached. Let us give the essential description of the different phases

3.1 The initialization phase

The manager consults the portal of the CIS (first assumption) to obtain useful informations on agents. Then, it decomposes the global task into subtasks w.r.t. the agents' industry branches. For each subtask, the manager makes a set of the candidates among agents of the environment.

3.2 The negotiation phase

The manager simultaneously sends the proposals to agents of the same set. The message which the manager sends to the candidates must contain all information about the cooperation project, as well as the waiting period that accords to them. Then, the manager receives the responses from the candidates. Figure 1 represents the state transitions for a negotiation between a manager *(m)* and a candidate *(c)*. After receiving a proposal from a manager for cooperation, a candidate can:

- *refuse to cooperate (refuse(c, m));*
- *accept to achieve the subtask (accept(c, m));*
- *accept to achieve the subtask and also propose to achieve another subtask(s) (ok(c, m));*
- *refuse to achieve the subtask but propose to achieve another subtask(s) (no(c, m));*
- *not answer. In this case, after the expiry of a waiting period, the manager considers the not reply as a rejection (refuse(c, m)).*

If the candidate agrees to cooperate, it must send to the manager a message that contains its consideration of the cost and the time for achieving the subtask, as well as the maximum reply time that it grants to the manager to evaluate the proposal.

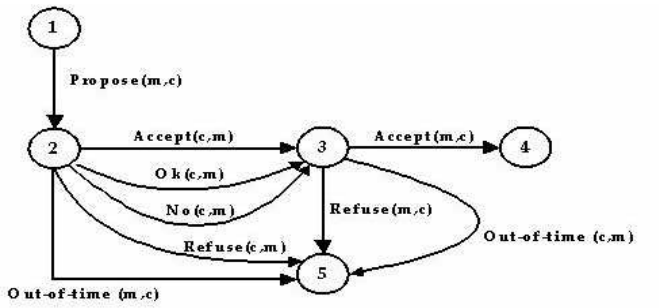

Figure 1: State transition graph of the negotiation between the manager (m) and a candidate (c)

3.3 The evaluation phase

After receiving the candidates' responses, the manager evaluates and classifies them according to their importances. The evaluation is made using a multicriterion analysis. This phase includes two stages. The first one deals with the evaluation of the criteria and the second one with the aggregation of the evaluations.

Criterion evaluation

In this stage, the manager evaluates agents which sent their proposals according to various criteria. In [11], the author defines a whole of interesting criteria for the selection of the most adequate partner. We select those which seem most significant to our context. We have classified the criteria into three categories:

(a) Criteria related to the partner

- the cooperation degree of the candidate agent with the manager (D1)

- the cooperation degree of the manager with the candidate agent (D2)
- the quality of the relation (D3) deduced from three others subcriteria:
  (i) respect of the allowed time for achieving the subtask (S1)
  (ii) the quality of achieving the subtask (S2).
  (iii) Honesty with regard to the profit distribution after the last experiment (S3)
- the experiment in the cooperation:
  (i) the cooperation number carried out by the partner (A1)
  (ii) the cooperation number carried out by the partner without interruption (A2).

(b) Criteria related to the cooperation
- the capital (C1).
- the technical capacity (C2).
- the technological competencies (C3)
- the existence of a single capability (C4).

(c) Criteria related to the candidate agent proposal The candidate must specify in its acceptance message the time *T* and the cost *C* for achieving the subtask.

The aggregation stage

After the evaluation of the different criteria, the manager incorporates the evaluations associated with all the criteria in order to have an overall estimate of each agent. In CFoTACIS, the aggregation of the criteria is used in two cases:

(i) For the trust quantification: The trust *e*, which results from the current relation with the agent partner, is carried out using the equation

$$e = p_1 * S_1 + p_2 * S_2 + p_3 * S_3$$

Where p_1, p_2, and p_3 are the weights that the agent must specify and $p_1+p_2+p_3=1$.

(ii) For the evaluation of each candidate: the aggregation operator is defined using a deviation at an aspiration point which gathers the preferred values of the criteria [12]. The evaluations are represented using a vector named b. The deviation b to the aspiration point a is defined by the relation.

$$deviation(a,b) = Max_{j=1..p}(\lambda_j(a_j - b_j))$$

With $\lambda_j = 1/(Ideal_j - AntiIdeal_j)$ and *p* is the number of criteria. *Ideal* is a vector which gathers the maximal criteria values of the evaluation vector and *AntiIdeal* is a vector which gathers the minimal criteria values of the evaluation vector.

The best evaluation d* is that which minimizes the deviation to the aspiration point:

$$d^* = min\{ deviation(a,b)\}$$

For well explaining the evaluation mechanism, let us consider the following example. Agents *Ag1*, *Ag2*, and *Ag3* are evaluated according only to the criteria *criterion1*, *criterion2*, and *criterion3* in the vectors *eval1*, *eval2*, and *eval3* (table 1).

Agents	Ag1		Ag2		Ag3		Ideal	antiIdeal	λ
Criterion	eval1	λ(Ideal-eval1)	eval2	λ(Ideal-eval2)	eval3	λ(Ideal-eval3)			
Criterion1	0.18	0	0.10	1	0.14	0.50	0.18	0.10	12.5
Criterion2	0.16	0	0.12	1	0.15	0.25	0.16	0.12	25
Criterion3	0.10	1	0.18	0	0.15	0.375	018	0.10	12.5
deviation	1		1		0.50				
d*	0.50								

Table 1: An illustrative example of the adopted aggregation operator

3.4 The finalization phase

After evaluating agents' proposals, the manager classes agents in a list according to their deviations. The manager sends the agent which is at the head of the list a message for inviting it to join the coalition; else it contacts the next agent in the list, and so on.

The coalition members merge their deviation vectors to have a unified view of the candidates. This merger allows the coalition members to have supplemented information since agents have only a partial vision of their environment. The merger is carried out by the *minimum operator*. Let us consider an example showing how to make the unified evaluation vector. Agent *Ag3* is evaluated by the members *Ag1* (eval1) and *Ag2* (eval2) w.r.t. to the eleven (11) criteria (see section 3.3.1).

eval1= (0.32, 0.56, 0.88, 20, 10, 2000, 1500, 5, 1, 0.53, 0.23)

eval2= (0.56, 0.12, 0.68, 20, 10, 2000, 1500, 5, 1, 0.53, 0.23)

The unified deviation vector is

eval= (0.32, 0.12, 0.68, 20, 10, 2000, 1500, 5, 1, 0.53, 0.23)

Thus, for each subtask, the coalition members together try to choose the adequate partner.

The negotiation process will be finished when the coalition size is reached, and therefore, the coalition members start the execution of the tasks. Hence, with CFoTACIS, the decision of the coalition structure is collective.

4 The CFoTACIS Properties

The proposed model presents several advantages. The choice of the partners is carried out by the coalition members thanks to the unification process of agents' estimates carried out by each member. The adopted aggregation operator does not authorize the compensation, which permits to choose a partner which has acceptable values for all the criteria. CFoTACIS ensures the equity property because it offers the same chances to the candidates by limiting the time of the binary negotiations. When the candidate specifies its waiting time, this avoid the coalition members to send message to an agent that is no more waiting. Consequently, a considerable profit of time will be obtained. When a partner disengages, it is obvious that it will be sanctioned. This sanction is expressed by the A2 parameter (see section 3.3.1.a). In this case, the coalition members have two alternatives for replacing the disengaged agent. They propose the subtask to the coalition members to cheek whether it exists a partner which is interested to achieve it. Therefore, a new negotiation process is avoided. The second alternative is applied when there are not members which are interested. The coalition is obliged to start a new negotiation process to find another partner. Finally, if the manager could not find partners or the required size of the coalition is not reached; the negotiation process will be remade.

5 Experimental results

We have implemented CFoTACIS using JADE 3.0 (Java Agent DEvelopment). We have compared its performances with those of a similar model [3]. We remind that in [3], the author proposed two

negotiation models. We are interesting to the one dedicated to egoistic agents considering the rationality of our agents.

We have made several series of experiments. In this paper, we show the effect of varying the agents' and subtasks' number on the global time of the negotiation process (figures 2 and 3).

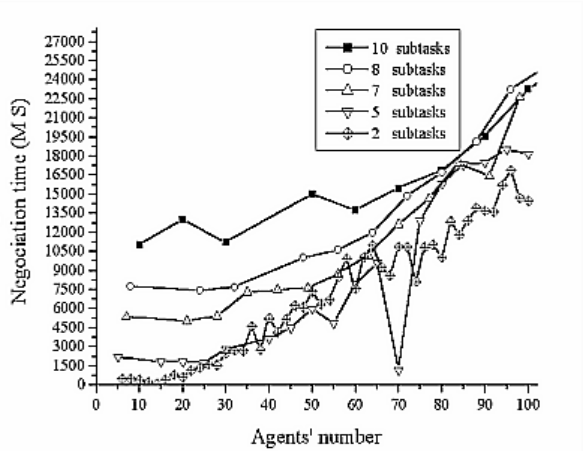

Figure 2: The negotiation time versus the agents' number for different subtasks' number in CFoTACIS

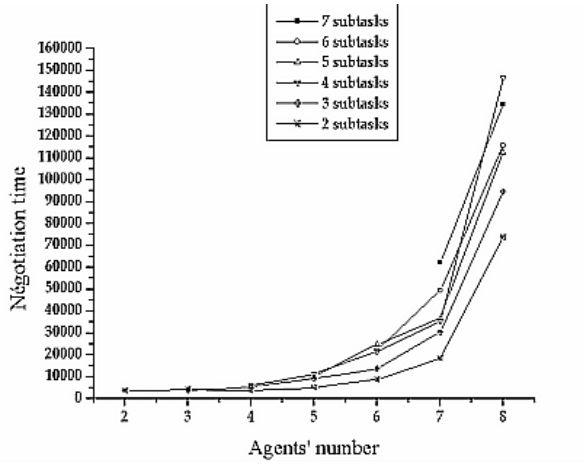

Figure 3: The negotiation time versus the agents' number for different subtasks' number in the model proposed in [3]

In each negotiation process, we fixe the subtasks' number and we increase the agents' number to finally deduce the consumed time. The graphs presented in this section are drowning using the Origin 6.0 software.

On the graph of figure 2 (CFoTACIS), we observe that we could vary agents' number from 2 to 100 and subtasks' number from 2 to 10. Whereas, on the figure 4 (the comparative model), we could vary agents' number only from 2 to 8 and subtasks' number only from 2 to 7. Therefore, we deduce that the CFoTACIS' scalability is stronger than the one of the comparative model. One reason of this result is that in the comparative model, all agents are in competition for the coalition formation. So, if we have "*n*" agents in the system, we have also "*n*" parallel negotiations which cause a scheduling problem in the system. On the other hand, we observe that the negotiation time in CFoTACIS increases as agents' and

subtasks' number increase. But this increase stills reasonable and very small in comparing it with the one of the comparative model. This is due to the weak scalability of the last one. Also, in the comparative model, there is no limitation of the negotiation time between agents

6 Summary and Conclusions

In this paper, we have proposed a coalition formation-based negotiation model for the cooperative information agent-based systems, named CFoTACIS. The proposed model is inspired from the reality of the cooperation between enterprises. It includes four phases, the initialization, the negotiation, the evaluation, and the finalization. The essential properties of CFoTACIS are its consideration of the preferences of the coalition members for choosing the future partners. It does not apply any authority on agents and ensures the equity by limiting the time of the binary negotiations due to the absence of the cycles in the proposed negotiation protocol. However, it does not ensure the reach of a consensus but tries to encourage agents to cooperate. The simulation results show that in CFoTACIS the spent time for the negotiation is reasonable and the messages' number is deterministic. These results have been confirmed by comparing the CFoTACIS' performances with those of the negotiation model proposed in [3].

In the future work, we will improve CFoTACIS so that it will ensure the reach of a consensus. Also, we will adopt it in other application fields like e-commerce.

References

[1] L. Putnam, M. S. Pool, "Conflict and Negociation In Handbook of Organizational Communication: An Intersciplinary Perspective," *F.M.Jablinetal, Eds. Saga Newbury Park,*, pp. 549-599, California, 1987.

[2] T. Sandholm, "An Algorithm for Optimal Winner Determinism in Combinatorial Auctions," *In Proc. of the 16th Int. Joint Conf. on AI, Stockholm, Sweden,*, 1999.

[3] S. Aknine, "Modèles et méthodes de Coordination des Systèmes Multi Agents," *Thesis of Doctorate, University Paris IX Dauphine-UFR Science of the Organizations,*, December 2000.

[4] N. Zarour, M. Boufaida, and L. Seinturier, "A Negotiation Framework for Organizational Information Systems," *Int. Journal of information Technology and Decision Making (IJITDM). World Scientific Publishing Co,*, vol. 3, nř2, pp. 213-238, June 2004.

[5] A. E. F. Saghrouchni and S. Haddad, "Recursive Model for Distributed Plannin," *In Proc. of the 2nd Int. Conf. On Multi-Agent Systems (ICMAS'96),*, AAAI Press. Kyoto, Japan, 1996.

[6] C. Brooks and E. Durfee, "Congregating and Market Formation," *Proc. of the 1st Int. joint conf. on Autonomous Agents and Multiagent systems,*, ACM Press, pp 96-103, 2002.

[7] A. E .F. Saghrouchni and G. Vauvert, "Formation de Coalitions pour Agents Rationnels," *In Proc. of ILIPN'2000. VIIIth days of LIPN. Multi-Agent Systemes and Formal Specification and Software Technologies* ,,Viltaneuse, France 09, 11-12, 2000.

[8] L. K. Soh, C. Tsatsouli, and H. Servey, "A Satisficing Negotiated and Learning Coalition Formation Architecture," *In V.Lesser, C.Ortiz, and M.Tambe, editors, Distributed Sensor Networks: a Multi-Agent perspective,*,Kluwer Academic Publishers, 04, 25-27, 2001.

[9] L. Larson and T. Sandholm, "Anytime Coalition Structure Generation: an Average Case Study," *Journal of Experiments and Therotical Al,*11, 1-20, 2000.

[10] Vassileva, J. Breban and S. Horsch, "Agent Reasoning Mechanism for Long-Term Coalitions Based on Decision Making and Trust," *Computational Intelligence, 18, 4, Special Issue on Agent Mediated Electronic Commerce,*, pp 583-595, Nov. 2002.

[11] C. Li and K. Sycara, "A Stable and Efficient Scheme for Task Allocation via Agent Coalition Formation," *www.2.cs.cmu.edu/ softagents/papers/CCO3.pdf,*, 2003.

[12]] N. R. Jennings, P. Faratin, P. Johnson, M. J. O'Brien, and M. Wiegand, "Using Intelligent Agents to Manage Business Processes," *Practical application of intelligent Agents and Multi-Agents technology, PAAM 96,*1999.

Nacer eddine Zarour, Sabrina Bouzidi
University Mentouri of Constantine
LIRE Laboratory, 25000 Algeria
E-mail: nasro_zarour@yahoo.fr, sab_bouzidi@yahoo.fr

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65 Years from Birth of Prof. Gheorghe S. Nadiu (1941-1998)

Ioan Dziţac, Loriana Andrei

Abstract: In 1967, Gheorghe S. Nadiu publishes in "Mathematical studies and researches", the article "On a method for the construction of Three - valued Łukasiewicz algebras" (Romania), cited in the book "Cylindric Algebras" by P. Monk, L. Henkin, A. Tarski. This article attracted the attention of Grigore C. Moisil, who offers him a scholarship, taking him out of production to make his doctorate at the Mathematic Institute of the Romanian Academy. He publishes more than 50 scientific papers in Theory of Algorithms, Logics of mathematics and Theory of Categories fields.
"Gheorghe S. Nadiu, by introducing the notion of quantified filter in a boolean monadic algebra, showed how one can obtain a trivalent Łukasiewicz algebra; also, he obtained an algebraic characterization of a completitude theorem from the intuitionist logic of Kripke." (G. St. Andonie, Science History in Romania, Academic Publishing House, SRR, 1981).

PhD Student Gheorghe Nadiu (1970)
at Mathematical Institute
of the Romanian Academy

Prof. univ. dr. Gheorghe Nadiu (1997)
Director of Mathematics Department
University of Oradea (1990-1994, 1996-1998)

1 Biographical dates

Name and surname: Nadiu Gheorghe
Date and place of birth: 1941, September, 12, Comlăuş-Sântana, Arad County, Romania
Date and place of dead: 1998, November 7, Oradea, Bihor County, Romania
Wife: Nadiu Doina Elena
Children: 1. Loriana; 2. Adina
Fields of Scientific Research: Theory of Algorithms, Mathematical Logic, Category Theory

1956-1959: Pupil at "Moise Nicoară" High School, Arad, Arad County, Romania
1959-1964: Student at Faculty of Mathematics and Physics, “Babes-Bolyai” University of Cluj
1964-1969: Assistant Professor at Pedagogical Institute of Oradea, Bihor County, Romania
1969-1972: PhD student at Mathematical Institute of the Romanian Academy (supervisor prof. Grigore C. Moisil)
1972: He obtain PhD in Mathematics with the PhD Thesis: “Cercetări asupra logicilor necryssipiene” / “Research about Necryssipiene Logics” (supervisor Grigore C. Moisil)
1973-1978: Lecturer at Pedagogical Institute of Oradea
1980-1990: Associate Professor at Pedagogical Institute of Oradea
1990- 1998: Professor at University of Oradea.

2 Didactical and managerial activity

After graduating the Faculty of Mathematics-Physics at the “Babeş-Bolyai” University of Cluj, in 1964, Gheorghe S. Nadiu becomes teaching assistant at the Pedagogic Institute from Oradea, job in which he functions until 1969, holding seminars of Theory of Probabilities, Differential equations, Theoretical mechanics and in the University Year 1968/1969 he teaches the course “Fundamentals of Mathematics”.

During 1969-1972 he is taken out of Education after obtaining a scholarship for executing the doctorate in mathematics under the scientific leading of professor Grigore C. , Moisil, at the Mathematic Institute of the Romanian Academy.

In 1972, after obtaining the title of Doctor in Mathematics, (Mathematical Logics) he comes back to his old workplace where he gets, through contest, a job as lecturer for the disciplines “Fundamentals of Mathematics” and “Mathematical Logics” which he teaches until 1978.

In 1978 he becomes titular of the courses “Superior Mathematics” and “Computer programming”, and in 1980 he occupies by contest the job as readership, on which he functions until 1990 when he obtains, by contest, the didactic title of University professor.

In 1990 the Institute from Oradea changes into University, and professor Nadiu becomes headmaster of the Mathematics Department of the University of Oradea, which he founds starting from a department with 2 personnel and develops until obtaining a department of over 30 personnel who operates in the whole University, and which he leads between 1990-1994 and 1996-1998.

Between 1990-1998 he teaches the courses “Mathematical Logics” and “Functional Analysis” at the Science Faculty of the University of Oradea, at the specializations mathematics-informatics and mathematics-physics.

He dies prematurely, at the early age of 57, because of cardio-respiratory death, still in full didactical working potential and creative scientific activity.

3 Scientific activity

In his first published scientific work [1], written as student, in collaboration with prof. Petre Brďeanu from Cluj, he presents an optimal moving regime of the ballistic missile, under the form of periodical functioning of exponential type of the engine, with help of the maximum principle of Pontriaghin.

The main directions of scientific research of Gh. Nadiu were directed to the Theory of Algorithms, Logics of mathematics, and Theory of Categories.

In the works [2,4] and [5], from the field of algorithms theory, first, there is given a double recursion theorem, in sense of Asser’ recursion theorem, and then a localization procedure of algorithms of Nogornâi type through the medium of Cernevski type, introduced by the author, as well as the construction of a universal Turing machine for the normal class algorithms of A. A. Markov.

In the field of mathematical logic Nadiu introduces in [3] an algebraic method of construction of trivalent Łukasiewicz algebras, starting from the monadic boolean algebras, by means of quantified filters introduced by him. This result is quoted in the treaty "Cilindric Algebras" by Henkin, Monk and Tarski [8]. Afterwards, the results are taken over in some researches of Luiz Monteiro from the University Bahia Blanca from Buenos Aires, Argentina.

Then, in [7], [9] and [10], there is given an interpolation theorem of Craig type for the strict positive logic and also a series of results of relative categorical order at the category of models for elementary logic of Moisil.

In the doctoral dissertation "Research on necryssipic logics" [11] elaborated under the scientific leadership of Grigore C. Moisil, sustained in 1972, G.S. Nadiu introduces the notion of "abstract calculation of superior order" as general developing frame of logic systems and gives then extensions of Moisil's modal logics and of logic of Nelson's and A. A. Markov's false constructible, the results are being found in [16].

In the same [11], Gh. S. Nadiu treated also S. Kripke theorem of completitude for Heyting intuitionist logic, from point of view of topological models. After this, he studies the pseudo - boolean pre - fascicle introduced by him through analogy with the Kripke models, for which he gives a series of categorical properties.

The results obtained by Gh. Nadiu in his doctoral dissertation [11] and published in "Logique - Automatique - Informatique" (1971) are in concordance with the results contained in the work of David P. Ellerman [12], which treats a particular case of pseudo - boolean pre - fascicle with values in the category of relational structures.

The studies of formal systems, in categorical sense, lead Gh. Nadiu to results related by the closed Cartesian categories [14] and to the obtaining of an exponentation theorem Birkoff type, in such categories as well as also to the development of the skolem pre - fascicle theory, introduced by him in [18, 20, 21, 22] which led him to fiber categories.

The algebraic study of the polyvalence in sense of Moisil's ideas led him to the introduction of notions of lattice under - reziduate Skolem [23].

In the ulterior works he developed the correspondence category and of general correspondence, ulterior applied at the monad theory.

Also, in the sense of Fröllich formal group, he gave a characterization of formal commutative Moufang curls [15], introduced by S. Basarab.

After 1980 his researches have been oriented to the study of the influence of mathematic logic in various branches of mathematics: functional analysis, algebra, auto-reglation problems in the theory of abstract automatics, model theory for theories with more variable sorts with application at the normative spaces theory.

References

[1] P. Brădeanu, Gh. S. Nadiu, *Asupra unui regim optim de mişcare a rachetelor balistice*, An. Univ. din Timişoara, vol. III, 1965.

[2] Gh. S. Nadiu, *Asupra unei teoreme de recursie a algoritmilor normali*, Studii şi cercetări matematice (Mathematical Reports), Tom. 18, 1966/7, pp. 1071.

[3] Gh. S. Nadiu, *On a method for the construction of three-valued Łukasiewicz algebras (Romanian)*, Studii Cerc. Mat., 19, 1967, 1063-1070.

[4] I. Maruşciac, Gh. S. Nadiu, *O interpretare a algoritmilor, schemă-graf în legătură cu maşinile Turing şi algoritmi de tip Cernevski*, Studii şi cercetări matematice, Tom. 20, 1968/7.

[5] Gh. S. Nadiu, *The interpolation theorem in strict positive logic*, Bull. Math. Soc. Sci. Math. Roum., Tom. 13, 1968/2.

[6] Gh. S. Nadiu, *O maşină Turing universală pentru clasa algoritmilor normali*, Studii şi cercetări matematice, Tom. 21, 1969/1.

[7] Gh. S. Nadiu, *Sur la logique de Heyting, in "Logique-Informatique-Automatique"*, Ed. of Romanian Academy, Bucureşti, 1971.

[8] L. Henkin, J.D. Monk, A. Tarski, *Cylindric Algebras*, North-Holland, Amsterdam 1971.

[9] Gh. S. Nadiu, *Sur la logique de Heyting*, Abstract of IV Congress of logic, Bucharest, 1971.

[10] Gh. S. Nadiu, *Elementary logic and models*, Bull. Math. d Soc. Sci. Math. Roum., Tom. 15, 1971/1.

[11] Gh. S. Nadiu, *Cercetări asupra logicilor necryssipiene/Research about Necryssipiene Logics*, 1972 (PhD Thesis, supervisor Grigore C. Moisil).

[12] David P. Ellerman, *Sheaves of Structures and Generalized Ultraproducts*, Annals of Mathematical Logic, 7 (Dec. 1974), 163-195.

[13] Gh. S. Nadiu, *An abstract calculi of superior order*, Proc. of IV Congress of logic,„ London-Ontario, Canada, 1975.

[14] Gh. S. Nadiu, *O teoremă de exponenţiere în categorii cateziene*, Lucr. Şt., Institul Ped. Oradea, 1977.

[15] Gh. S. Nadiu, *Asupra buclelor Moufang formele comutative/Note sur les boucles Moufang formelles commutatives (Romanian)*, Stud. Cercet. Mat. 32, pp. 193-207, 1980.

[16] Gh. S. Nadiu, *Notă asupra spaţiilor metrice constructive*, Studii şi cercetări matematice, 1980.

[17] Gh. S. Nadiu, *Non-Clasical Logic of Superior Order*, Resegna internationale di logica, Bologna, Bull.Math., 1981.

[18] Gh. S. Nadiu, *Considerations sur les categories cartesienes fermes*, bull. math.

[19] G. St. Andonie, *History of sciences in Romania. Mathematics, mechanics, astronomy, (Istoria Ştiinţelor în România. Matematica, mecanica, astronomie)(Romanian)*, Bucuresti: Ed. Acad. R.S.R.,1981, pp.123.

[20] Gh. S. Nadiu, *Category of correspondence and extensions*, Jounal of pure and appl. Algebra.

[21] Gh. S. Nadiu, *On Boolean formal algebras*, Bull. Math. d Soc. Sci. Math. Roum., 1978.

[22] Gh. S. Nadiu, *Prefascicule peste latici Skolem (I)*, Lucrări Şt. ale Inst. de înv. sup. Oradea, 1978, ser. A, pp. 37-63.

[23] Gh. S. Nadiu, *Asupra laticilor Skolem*, Lucrări Şt. ale Inst. de înv. sup. Oradea, pp. 65-69, 1978.

[24] Nadiu, Gh.S., *Considerations in category of Skolem lattices*, (Romanian. English summary), Bul. Stiint. Inst. Politeh. Cluj-Napoca, Ser. Electroteh. Energ. Inf. 25, 29-36 1982.

[25] Gh. S. Nadiu, *Logici cu mai multe sorturi de variabile şi spaţii vectoriale*, în vol. Lucrările celui de al III-lea Simpozion naţional de analiză funcţională, Craiova, 6-7 nov. 1981.

[26] Gh. S. Nadiu, T Pop, *Automate-tehnologii şi decizii*, în vol. "Cibernetică aplicată", Bucureşti, Ed. Acad. R.S.R., 1983.

[27] Gh. S. Nadiu, *Aspecte booleene în categoria spaţiilor vectoriale normate*, în vol. Lucrările celui de al IV-lea Simpozion naţional de analiză funcţională, Craiova 6-7 nov. 1983.

[28] Gh. S. Nadiu, *Prefascicule peste latici Skolem (II)*, Lucrări Şt. ale Inst. de înv. sup. Oradea, seria A, 1978.

[29] Gh. S. Nadiu, *Asupra logicii modale generale a lui Moisil*, Lucrări Şt. ale Inst. de înv. sup. Oradea, seria A, 1978.

[30] Gh. S. Nadiu, *Asupra ordonărilor Rudin-Kreisler în clasa ultrafiltrelor*, Lucrări Şt. ale Inst. de înv. sup. Oradea, seria A, 1978.

[31] Gh. S. Nadiu, *Contribuţii la teoria relaţiilor (I)*, Lucrări Şt. ale Inst. de înv. sup. Oradea, seria A, 1980.

[32] Gh. S. Nadiu, *Contribu ctii la teoria relaţiilor (II)*. Corespondenţe via toposuri., Lucrări Ştiinţifice, Oradea, seria A, 1980.

[33] Gh. S. Nadiu, *O clasă specială de L-endometrici probabiliste*, Lucrări Ştiinţifice, Oradea, seria A, 1980.

[34] Gh. S. Nadiu, Gh. Niculae, *Funcţii parţiale injective şi filtre de compunere*, Lucrări Ştiinţifice, Oradea, seria A, 1980.

[35] Gh. S. Nadiu, *Notă asupra relaţiilor de secvenţă*, Lucrări Ştiinţifice, Oradea, seria A, 1979.

[36] Gh. S. Nadiu, Gh. Niculae, *Asupra categoriei-algebrelor*, Lucrări Ştiinţifice, Oradea, seria A, 1981-1982.

[37] Gh. S. Nadiu, *Notă asupra filtrelor într-o algebră Łukasievich 0-valentă*, Lucrări Şt., Oradea, seria A, 1981-1982.

[38] Gh. S. Nadiu, *Contribuţii la teoria relaţiilor (III). Interpretări sintactice*, Lucrări Şt., Oradea, seria A, 1981-1982.

[39] Gh. S. Nadiu, *Dinamica deciziilor*, Rezumat vol. Celui de al IV-lea Simpozion naţional de cibernetică, 1986.

[40] Gh. S. Nadiu, *Asupra noţiunii de topologie*, Simpozion naţional de topologie, Cluj Napoca, 1986.

[41] Gh. S. Nadiu, *Produse fibrate în categoria automatelor*, Comunicare la Conferinţa naţională de algebră, Timişoara, 1986.

[42] Nadiu, Gh. S., *On topologies and overtopologies* (English), Prepr., "Babes-Bolyai" Univ., Fac. Math. Phys., Res. Semin. 1988, No.2, pp. 121-126 (1988).

[43] Gh. S. Nadiu, Loriana Popa, *Asupra teoriei omotopiei*, Analele Univ. Oradea, III, pp. 12 - 19, 1993.

[44] Gh. S. Nadiu, *Notă asupra spaţiilor liniar normate*, Analele Univ. Oradea, I, pp. 91 - 94, 1991.

[45] Gh. S. Nadiu, *Consideraţii algebrice relaţii la cat. sp. metrice.*, Analele Univ. Oradea, II, pp. 99 - 106, 1992.

[46] Gh. S. Nadiu, *Dinamici. Aspecte categoriale*, Analele Univ. Oradea, III, pp. 1 - 12, 1993.

[47] Gh. S. Nadiu, *Consideraţii asupra categoriilor carteziene*, Lucrărrile CAIM 1996, pp. 201 - 207.

[48] A. Georgescu, C.L. Bichir, G.V. Cîrlig, *Matematicieni români de pretutindeni*, ED. The Flower Power, pp. 135, 2004.

[49] G. Georgescu, A. Iorgulescu, S. Rudeanu, *Grigore C. Moisil (1906 - 1973) and his School in Algebraic Logic*, Int. J. of Computers, Communications and Control, IJCCC Vol. I (2006), No.1, 81-89.

Ioan Dziţac
Agora University
8 Piata Tineretului 410526 ORADEA
ROMANIA
idzitac@univagora.ro

Loriana Andrei
University of Oradea
3-5 Universitatii St. 410087
ROMANIA

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