The Cooperative Cleaners Case Study: Modelling and Analysis in Real-Time ABS

Silvia Lizeth Tapia Tarifa

Precise Modelling and Analysis
University of Oslo

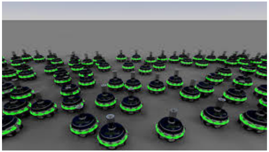
sltarifa@ifi.uio.no

29.11.2013

Outline

Swarm Robotics

Group of autonomous, simple and similar robots is coordinated in a way that leads to useful behaviour of the swarm itself.



Advantages

- Parallelism: robots cooperate and synchronise intelligently.
- Decentralised: robots operate on local information to accomplish global goals.
- Adaptability: changing environment.
- Scalability: e.g., number of robots.
- Fault-tolerance: robots complete the task, even if some of them fail.

ABS – Abstract Behavioural Specification Language

ABS is a language for modelling object-oriented systems at an abstract, yet precise level.

- Targets software systems that are:
  concurrent, distributed and object-oriented.
- Offers a wide variety of modelling options in one framework. (datatypes, functions, classes, concurrency, distribution, etc.).
- Clear and simple concurrency model that permits synchronous as well as asynchronous communication.
- Abstracts from implementation choices of data structures.
- Fully executable with code generators into e.g., Java and Maude.
- Has a formal semantics.

Real-Time ABS extends the syntax and semantics of ABS in order to allow models with time dependent behaviour.

About This Thesis

Questions:

1. How can Real-Time ABS be used to naturally model autonomous, decentralised and self-organised systems such as swarm robotics?
2. To what extent can the simulation tool of Real-Time ABS help to analyse the collective behaviour of such systems?

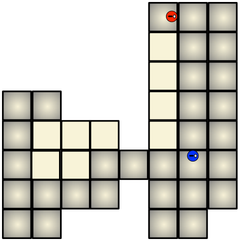
Approach:

- Develop a case study from the swarm robotics domain that exploits features of Real-Time ABS such as concurrency, distribution, object-orientation and so forth.
- Evaluate how well Real-Time ABS can be applied to model and analyse this case study.

The Cooperative Cleaners Case Study

A group of cleaning robots cooperate to clean a dirty floor

- Floor:
  connected dirty area in $\mathbb{Z}^2$.
- Cleaner:
  - restricted amount of memory,
  - indirect communication (signals and sensing),
  - local knowledge (e.g., overall topology of the dirty floor is unknown),
  - movement follows a protocol.

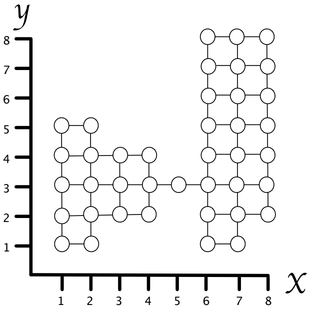


Cleaning the whole floor is
an emerging property of the cleaning robots cooperation

Original definition: Cooperative cleaners: A study in ant robotics. Israel A. Wagner, Yaniv Altshuler, Vladimir Yanovski, and Alfred M. Bruckstein, 2008.

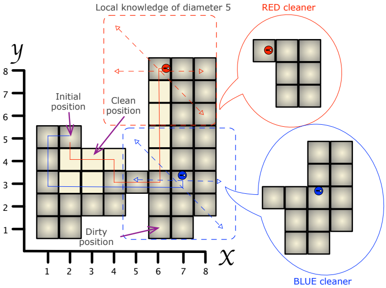
Definition of the Problem: The Floor

- Shape: undirected graph G in $\mathbb{Z}^2$ with vertices $v = (x, y)$ representing positions connected with edges $e = (v, w)$ following a *4-neighbours* relation.
- Concepts: *4-neighbours*, *8-neighbours*, *boundary*, *single connected component*, *critical* vertex.
- The dirty floor F_t is a subgraph of G, t represents time.
- Initial state: assume G is a *single connected component* without holes or obstacles, and $F_0 = G$.



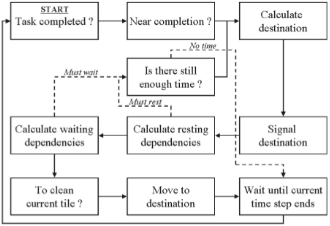
Definition of the Problem: The Cleaners

- Group of identical cleaners moving across F_t.
  (using *4-neighbours* relation).
- Cleaners can only observe their local environment.
- Goal: clean the dirty floor
  (not prior knowledge of
  the shape or size of the dirty floor).
- All the cleaning robots start and stop in the same position.
- Initial position: at the *boundary* of F_0.

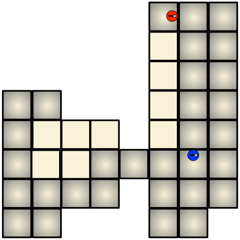


Definition of the Problem: The CLEAN Protocol

- Common protocol: moving and cleaning (non-critical positions) along the boundary of F_t.
- Cyclic algorithm: in each discrete time step, each cleaner executes one outer cycle.
- The cleaners "peel" layers from the boundary of F_t, until F_t is cleaned entirely.
- Protocol must preserve the connectivity of the dirty floor.



From: Cooperative cleaners: A study in ant robotics. Wagner *et al.*



The Cooperative Cleaners: Model in Real-Time ABS

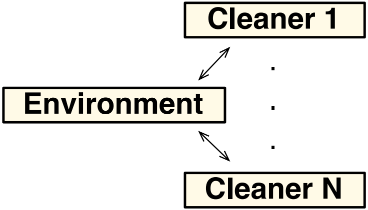
1. User-defined datatypes and their associated functions.
   - To represent and manipulate the information of the floor and the cleaners.
   - To record monitoring information.

```
type Pos = Pair<Int, Int>;
type Graph = Set<Pos>;
...
type CleanersPerPos = Map <Pos,Cleaners>;
...
type FloorPath = List<Triple<Time,Pos,String>>;
...
type CleanerPath = List<Pair<Time,Pos>>;
...
```

The Cooperative Cleaners: Model in Real-Time ABS

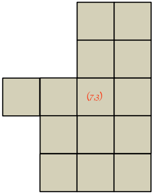
2. Abstracting hardware of cleaners and environment.

- Abstracted using method calls.
- Modelling entity environment.
- Passive floor vs. reactive environment.



The Cooperative Cleaners: Model in Real-Time ABS

3. Interpretation and implementation of informal concepts as functions.



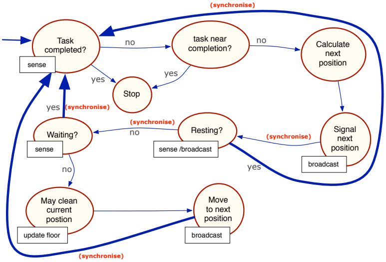
(x-1,y+1) up left	(x,y+1) up	(x+1,y+1) up right
(x-1,y) left	(x,y)	(x+1,y) right
(x-1,y-1) down left	(x,y-1) down	(x+1,y-1) down right

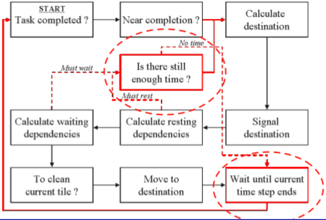
```
def PosSet eightNbr(Pos p, Graph g) =
  let (Pos u)=up(p) in
  let (Pos ul)=upleft(p) in
  let (Pos ur)=upright(p) in
  let (Pos l)=left(p) in
  let (Pos r)=right(p) in
  let (Pos d)=down(p) in
  let (Pos dl)=downleft(p) in
  let (Pos dr)=downright(p) in
  dirtySet(set[u,ul,ur,l,r,d,dl,dr],g);

def PosSet dirtySet ...
```

The Cooperative Cleaners: Model in Real-Time ABS

4. Ambiguities of the CLEAN protocol.

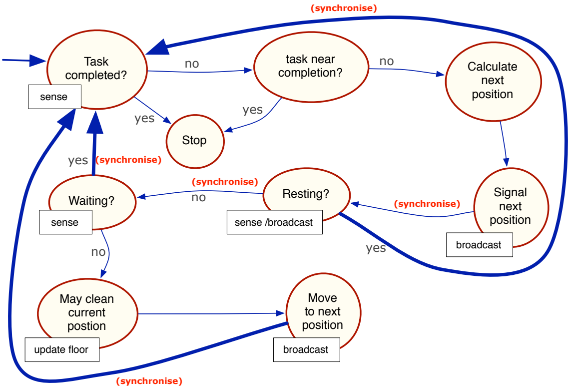
- Unexplained "Check Near Completion of Mission" subtask. SWEEP Protocol.
- Adaptation of the "Calculate waiting dependencies" subtask.
- Implicit synchronisation: we used fixed timers to guarantee homogeneous progress. We restricted the execution of the CLEAN protocol to only one cycle per time step.





The Cooperative Cleaners: Model in Real-Time ABS

4. Ambiguities of the CLEAN protocol.



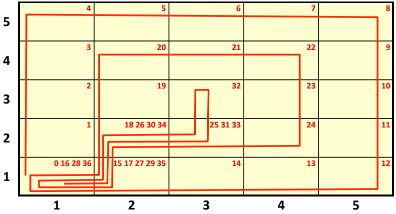
The Cooperative Cleaners: Analysis and Simulations

During the modelling process:

1. Validate that the manipulation of user-defined datatypes is correct.
2. Validate that the implementation of the concepts given in the problem description is adequate.
3. Observe that the recording of the monitoring information was consistent.
4. Observe that the model satisfies the considered safety properties.

The Cooperative Cleaners: Analysis and Simulations

Cleaning a five per five square floor using one cleaner



Path of the cleaner

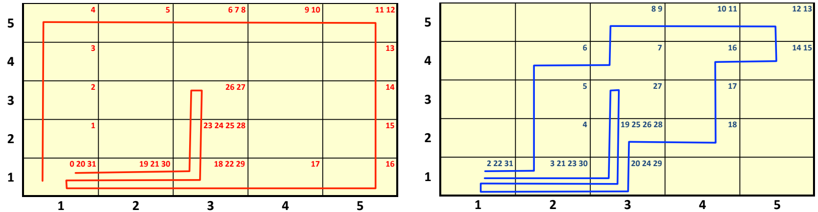
	1	2	3	4	5
5	4	5	6	7	8
4	3	20	21	22	9
3	2	19	32	23	10
2	1	34	33	24	11
1	36	35	14	13	12

Progress of cleaning the floor

Total time: 36

The Cooperative Cleaners: Analysis and Simulations

Cleaning a five per five square floor using two cleaners

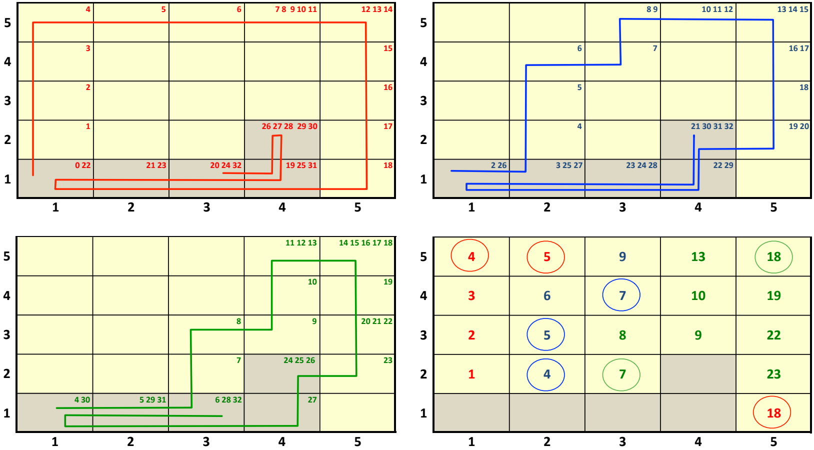


	1	2	3	4	5
5	4	5	9	11	13
4	3	6	7	16	15
3	2	5	27	17	14
2	1	4	28	18	15
1	31	30	29	17	16

Total time: 31

The Cooperative Cleaners: Analysis and Simulations

Cleaning a five per five square floor using three cleaners



The Cooperative Cleaners: Analysis and Simulations

Summary of simulation results.

5x5 (size = 25)	Time
1 cleaner	36
2 cleaners	31
3 cleaners	(before livelock) 23
10x10 (size = 100)	
1 cleaner	140
2 cleaners	129
3 cleaners	(before livelock) 83
20x20 (size = 400)	
1 cleaner	580
2 cleaners	587

Conclusions

Q_1. *How can Real-Time ABS be used to naturally model autonomous, decentralised and self-organised systems such as swarm robotics?*

Conclusions

Real-Time ABS & modelling of swarm robotic systems

- Special hardware. Entity *environment*.
- Passive environment. Entity *environment*.
- Implicit communication. Entity *environment*.
- State representation. User-defined datatypes.
- Work flow. Functional + Imperative.
- Monitoring information. User-defined datatypes.
- Synchronisation. Modelling a suitable synchronisation mechanism for a given concurrent problem represents a challenge on its own (e.g., fixed timers).

Conclusions

Q_1. *How can Real-Time ABS be used to naturally model autonomous, decentralised and self-organised systems such as swarm robotics?*

A_1. From the cooperative cleaners case study:

- almost naturally model in Real-Time ABS (simple concurrent model, functional layer, imperative layer),
- it required fairly advanced modelling skills.

Conclusions

Q_2. *To what extent can the simulation tool of Real-Time ABS help to analyse the collective behaviour of such systems?*

Conclusions

RTABS & analysis of swarm robotic systems

- Simulations.
  - Useful while modelling the case study.
  - Limitations with respect to handling large amount of data.
- Analysis of monitoring information.
  - Insights about the behaviour of the system.
  - Manual analysis.
  - Output format from the tool is not user friendly.
  - Hard to scale in the size of the floor and
    in the number of cleaners.

Conclusions

Q_2. *To what extent can the simulation tool of Real-Time ABS help to analyse the collective behaviour of such systems?*

A_2. From the cooperative cleaners case study:

- can be analysed using simulations,
- restricted analysis to small scenarios,
- requires reformatting and reorganisation of obtained monitoring data.

Future Work

- Possible changes to the model and to the protocol itself.
  - Group of robots with coordinators.
  - Different synchronisation mechanisms (e.g., flexible timers).
- Possible extensions to the analysis,
  using symbolic execution.
  - Reasoning about invariants using KeY.
  - Reasoning about cost analysis using COSTA.

THANK YOU