Analysing Robot Swarm Decision-making with Bio-PEPA

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joint work with
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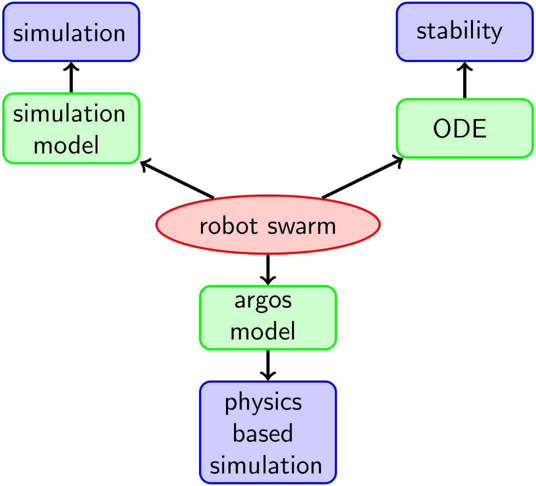
Swarm Robotic Systems Analysis



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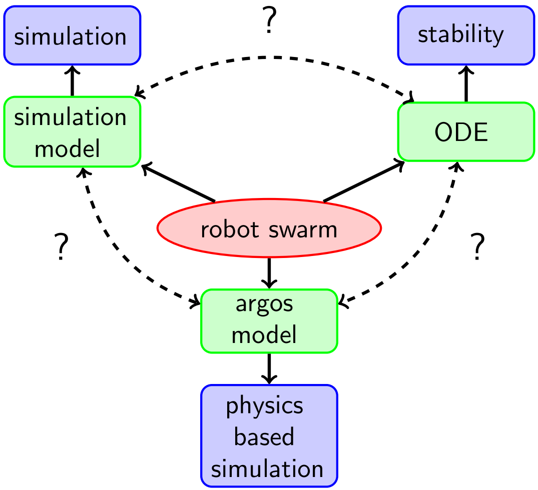
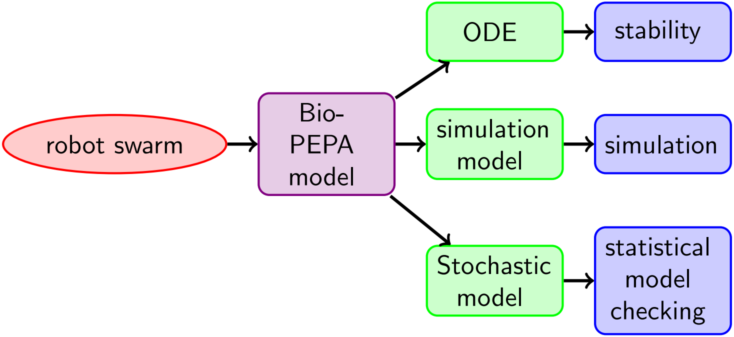
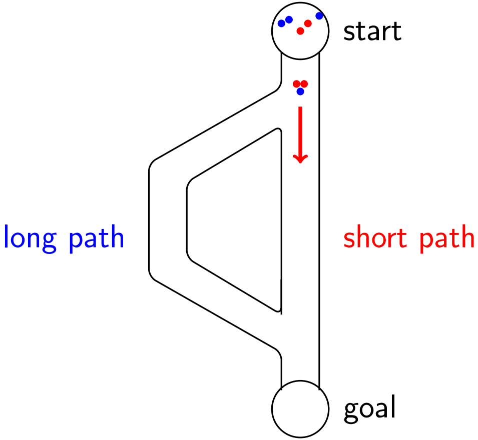




- Consistency: formal relation between models and analyses results
- One model using agent based perspective and composition
- Scalability: abstraction from agent identity
- Design phase analysis: select most promising solutions for further study

Swarm Decision Making [Montes de Oca et al., 2011]

Variant of the well-known double bridge experiment:



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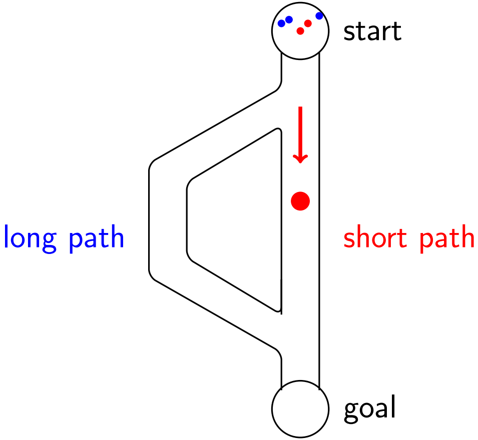

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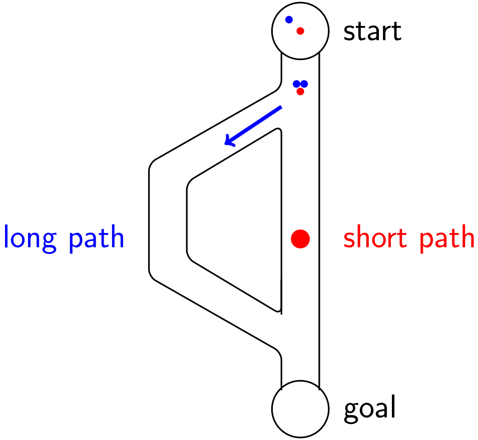

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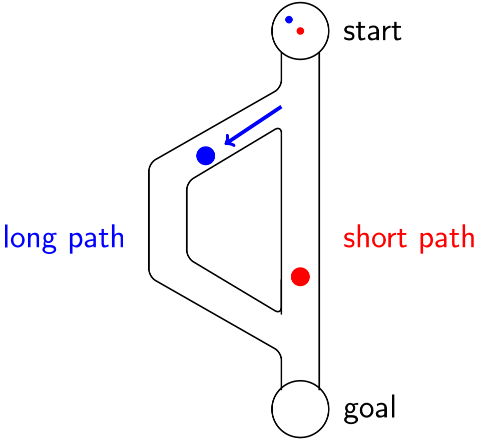

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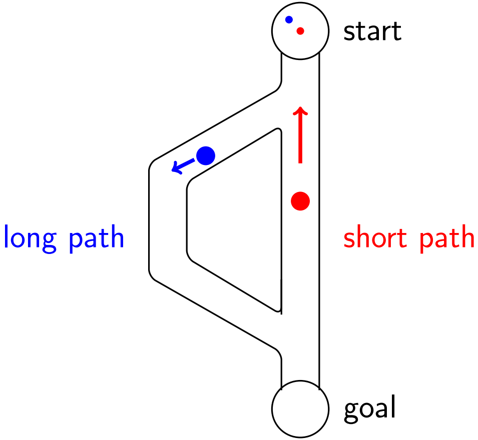

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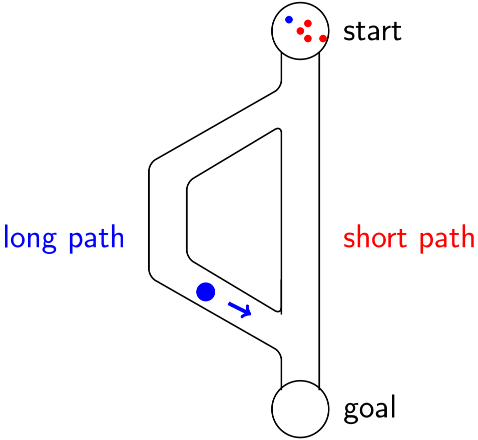


Challenge

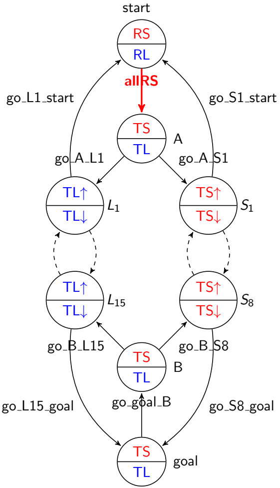
"Can formal methods contribute to model and analyse the emergent behaviour of agent-based Robot Swarms?"

- Can emergent behaviour in time and space be addressed?
- Is the method scalable?
- Can we deal with the formation of teams of robots?
- Can we handle action durations in a sufficiently accurate way?
- Can we deal with spatial aspects?

- What is the probability of convergence on each path?
- What are the average number of teams formed until convergence?
- How much time passes before convergence occurs?
- What is the average transient behaviour of the system?

Bio-PEPA model of Swarm Decision Making

[Bio-PEPA: Jane Hillston et al., 2009]



location top : *size* = 10000, *type* = *compartment*
location start in top : *size* = 1000, *type* = *compartment*
. . .
*location L*15 *in top* : *size* = 1000, *type* = *compartment*
location goal in top : *size* = 1000, *type* = *compartment*

$$
\begin{aligned}
Robo\_start\_fromS \;=\;& (allRS, 3)\downarrow Robo\_start\_fromS@start + \\
& (RS2RL1, 2)\downarrow Robo\_start\_fromS@start + \\
& (RS1RL2, 1)\downarrow Robo\_start\_fromS@start + \\
& (go\_S1\_start, 3)\uparrow Robo\_start\_fromS@start;
\end{aligned}
$$

$$
\begin{aligned}
Teams\_A\_S \;=\;& (allRS, 1)\uparrow Teams\_A\_S@A + \\
& (RS2RL1, 1)\uparrow Teams\_A\_S@A + \\
& go\_A\_S1\downarrow Teams\_A\_S@A;
\end{aligned}
$$

$$
\begin{aligned}
Teams\_A\_L \;=\;& (allRL, 1)\uparrow Teams\_A\_L@A + \\
& (RS1RL2, 1)\uparrow Teams\_A\_L@A + \\
& go\_A\_L1\downarrow Teams\_A\_L@A;
\end{aligned}
$$

$$
\begin{aligned}
system \;::=\;& (Robo\_start\_fromS@start(SS) < * > Robo\_start\_fromL@start(SL) \\
& < * > \ldots < * > Teams\_B\_fromL@B(0))
\end{aligned}
$$

$$
\begin{aligned}
RSS &= Robo\_start\_fromS \\
RSL &= Robo\_start\_fromL \\
kineticLawOf\ \ allRS &: \frac{(RS)}{(RS)+(RL)} * \frac{(RS-1)}{(RS-1)+(RL)} * \frac{(RS-2)}{(RS-2)+(RL)} * move; \\
pSSL &= \frac{(RS)}{(RS)+(RL)} * \frac{(RS-1)}{(RS-1)+(RL)} * \frac{(RL)}{(RS-2)+(RL)} \\
kineticLawOf\ \ RS2RL1 &: (pSSL + pSLS + pLSS) * move; \\
kineticLawOf\ \ go\_A\_S1 &: walk * Teams\_A\_S@A;
\end{aligned}
$$

$SS = 16,\ SL = 16,\ move = 0.28,\ walk = 0.1,\ k = (32 - minstart)/3$

Validation of results

Three approaches:

- Stochastic simulation (Gillespie) via Bio-PEPA plugin tools
- Statistical model checking via Bio-PEPA tools + PRISM tool
- Fluid approximation (ODE) via Bio-PEPA tools

Download and info:

- `http://homepages.inf.ed.ac.uk/jeh/Bio-PEPA/biopepa.html`
- `http://www.prismmodelchecker.org`

Statistical Model Checking

e.g. [Peyronnet et al., 2004, Kwiatkowska et al., 2011]

Validation for values of k ranging from 1 to 10 (active teams) of the following quantitative properties [Montes de Oca et al., 2011]:

- Probability of convergence on short path
- Expected team formations until convergence
- Expected convergence time

There exist several variants of Statistical Model Checking.

We use the Confidence Interval (CI) method to approximate:

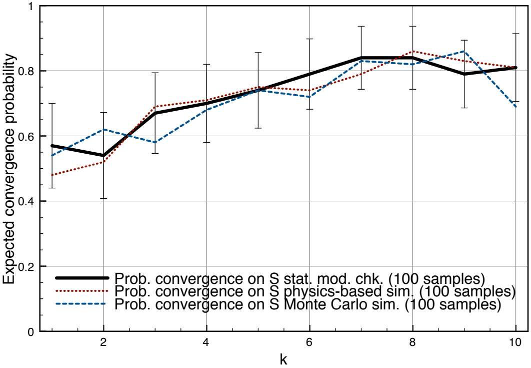
- Probability
- Rewards

SMC: Probability of convergence on short path

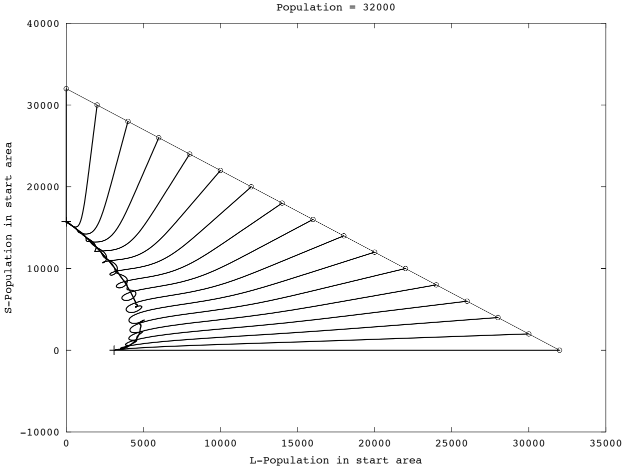
$$P =? [!\text{“}Convergence\_on\_L\text{”}\ U\ \text{“}Convergence\_on\_S\text{”}]$$

What is the probability ($P =?$) to see no (!) convergence on L until (U) convergence on S takes place?

“Convergence_on_S” = all the 32 robots are either in a team on the short path or in the S-population in the start area or at the goal area.



Fluid approximation (for k=7)



Phase-space diagram of S-population versus L-population in the start area for a population of 32,000 robots.

Conclusions and Discussion

Conclusions:

- Validation shows promising correspondence to results in the literature
- Modelling of populations, teams, locations, distances, probabilities
- Various analysis methods have been applied on same model
- Efficient analysis times, also addressing emergent behaviour

Discussion:

- Revisiting the language: 'Swarm-PEPA'? (WP4, T4.2)
- Further analysis techniques to support design of emergent behaviour? (WP3, T3.2)
- Spatial aspects of SRS: beyond simple locations? (Self)-Adaptive systems?
- Modeling language for autonomic systems?
  E.g. Service Component Ensemble Language (SCEL) language of EU ASCENS/QUANTICOL projects.