Swarm Engineering: a bio-inspired approach to resilient multi-robot systems

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UWE
University of the West of England
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This Talk

- In three parts:
  - About the Bristol Robotics Laboratory
  - Introduction to Swarm Robotics
    - Potential and Challenges
  - Case Studies in Swarm Robotics
    - Flying flock
    - Symbrion project
    - Artificial Culture project
    - Adaptive Swarm Foraging
    - In depth: Wireless connected swarm

About the BRL

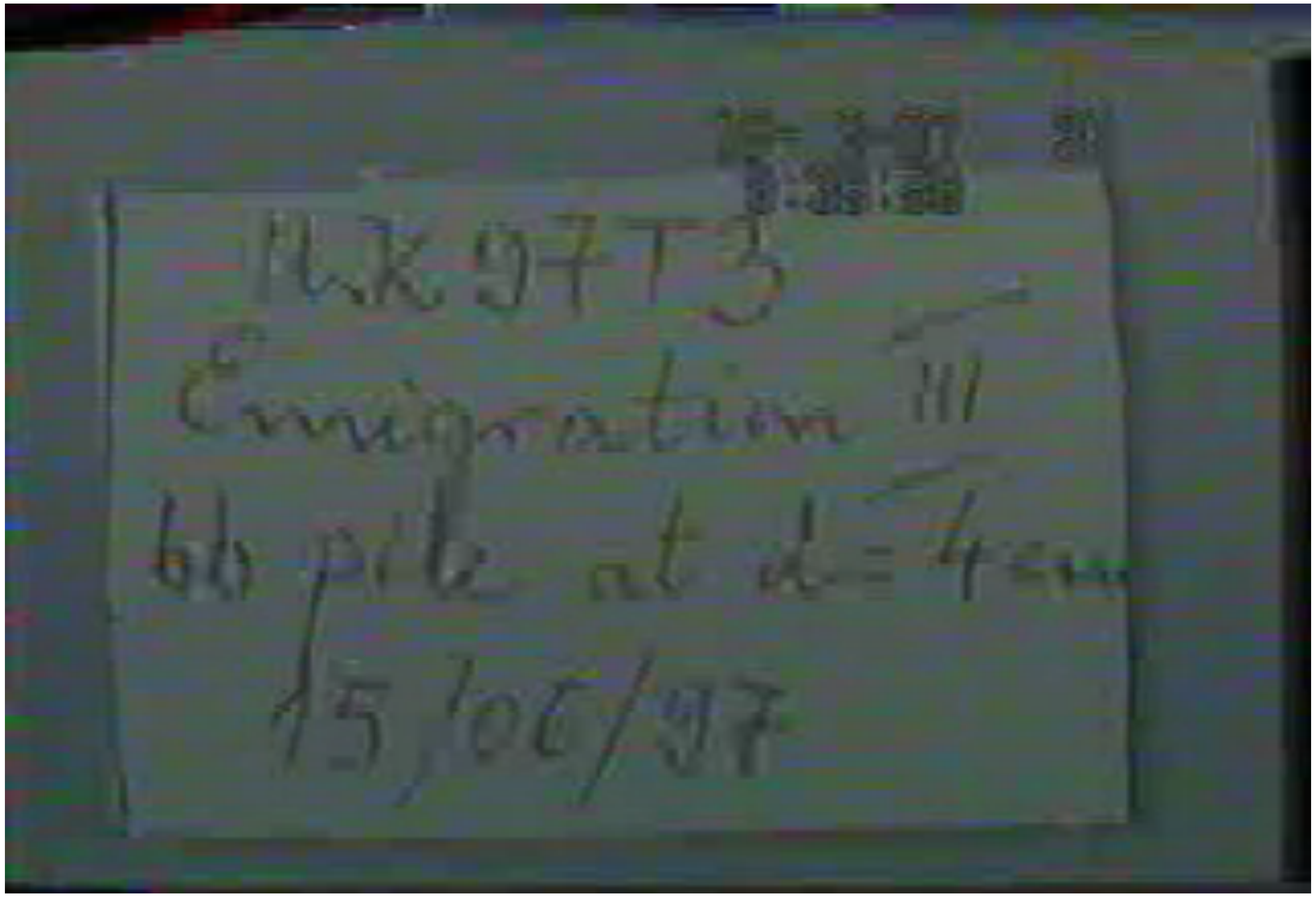
- Founded in 1993 as the Intelligent Autonomous Systems Lab
- The Bristol Robotics Lab is, since 2005, a joint research lab of UWE and the University of Bristol

Three main areas:
- Biological Robotics
- Human Robot Interaction
- Swarm Robotics

Strong focus on *real robot experiments*

Swarm Intelligence…

- *"Any attempt to design algorithms or distributed problem-solving devices inspired by the collective behaviour of social insect colonies and other animal societies"* *Bonabeau, Dorigo and Theraulaz, 1999*



Leptothorax at work

The Potential: Swarm Robotics is characterised by...

- Relatively simple, autonomous robots
- Fully distributed, de-centralised control
  - Exploitation of agent-agent and agent-environment interaction
  - Exploitation of explicit or implicit (stigmergic) communication
  - Self-organisation and emergence
- Scalability
- Robustness

But... can we engineer solutions with swarm intelligence..?

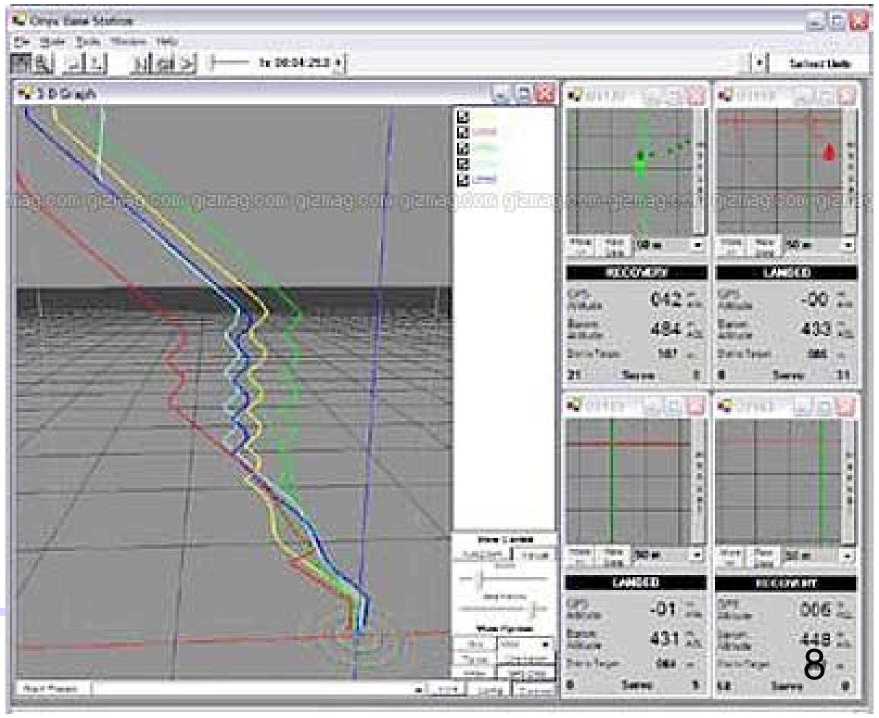
- What are the design principles involved?
  - how do we determine the *local rules* for each individual agent, in a principled way?
- How can we validate overall behaviours that are *emergent* properties?
  - notwithstanding these (difficult) questions...
- A powerful new engineering paradigm for large scale distributed systems..?

The Real-world Potential

- Any application requiring multiple distributed autonomous robots...
    - unmanned exploration/mapping/ surveying/environmental monitoring
    - robot assisted search and rescue
    - robot assisted harvesting/horticulture
    - waste processing/recycling
    - domestic or industrial cleaning
    - art and entertainment

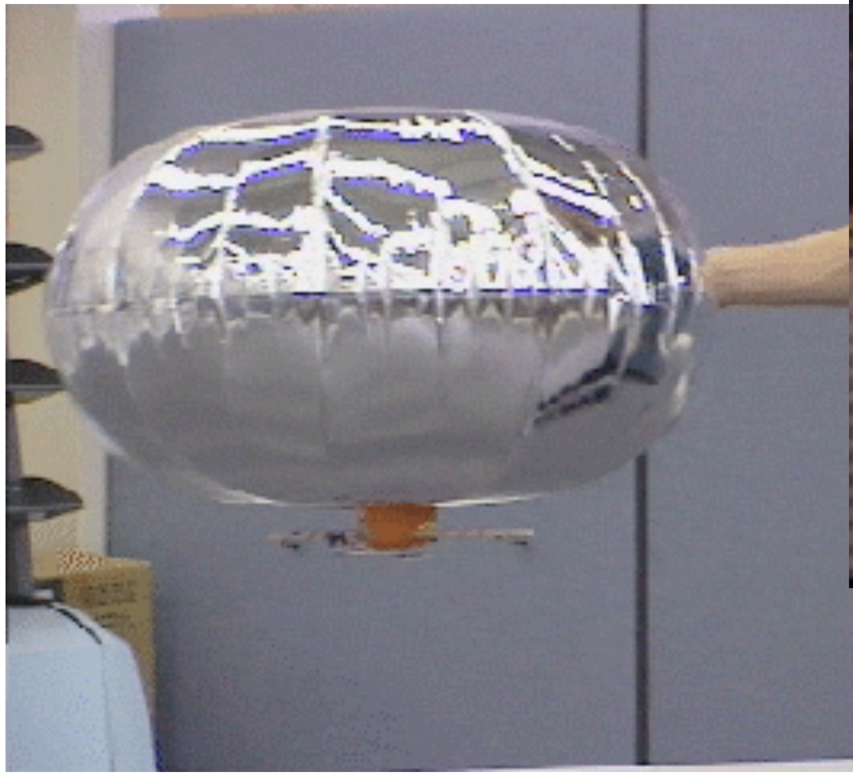
Real-world Applications

- At the time of writing there is only one known real-world application of swarm robotics
  - A swarm of autonomous parachutes for delivering supplies
    - the *Onyx* parachutes swarm to maintain proximity so that they will not be widely dispersed on landing
    - see http://www.gizmag.com/go/6285/



The Flying Flock Project: emergent control of groups of miniature helium-filled blimps (aerobots)

A flock of Starlings



The world's first flock of real (aero)bots in 3D [Welsby]

Symbrion

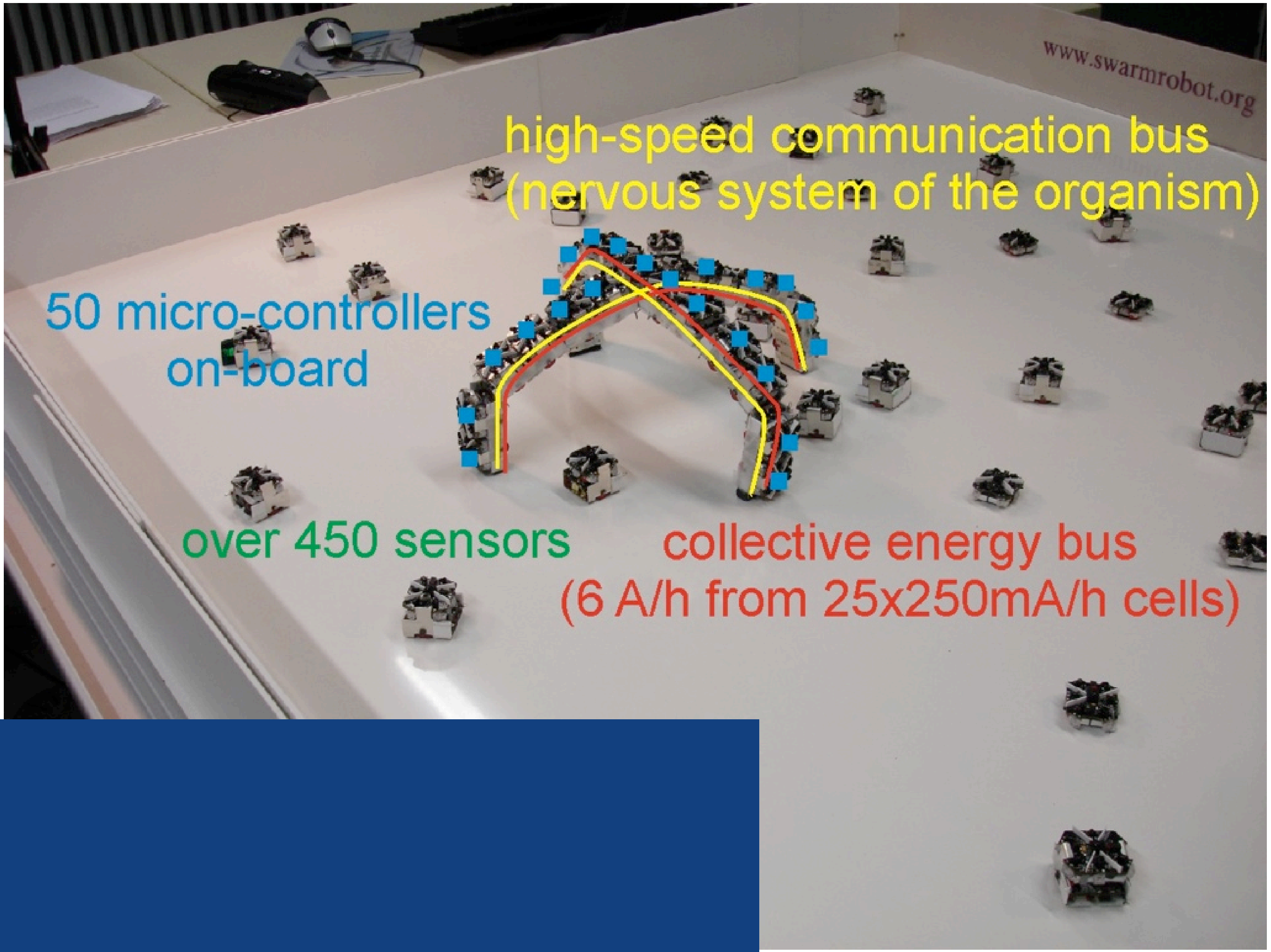
A 5 year project to build a Symbiotic Evolutionary Robot Organism

Individual robots are, in effect, ‘cells’ in a multi-celled organism, which

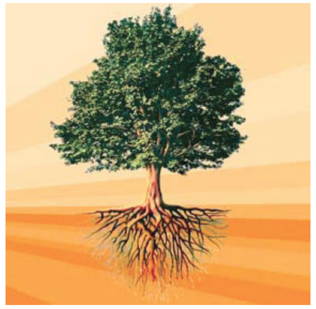
- ✓ self-assemble
- ✓ differentiate
- ✓ share resources
- ✓ evolve and adapt

The Symbrion organism could have, for example...

- ✓ homeostasis
- ✓ an auto-immune system

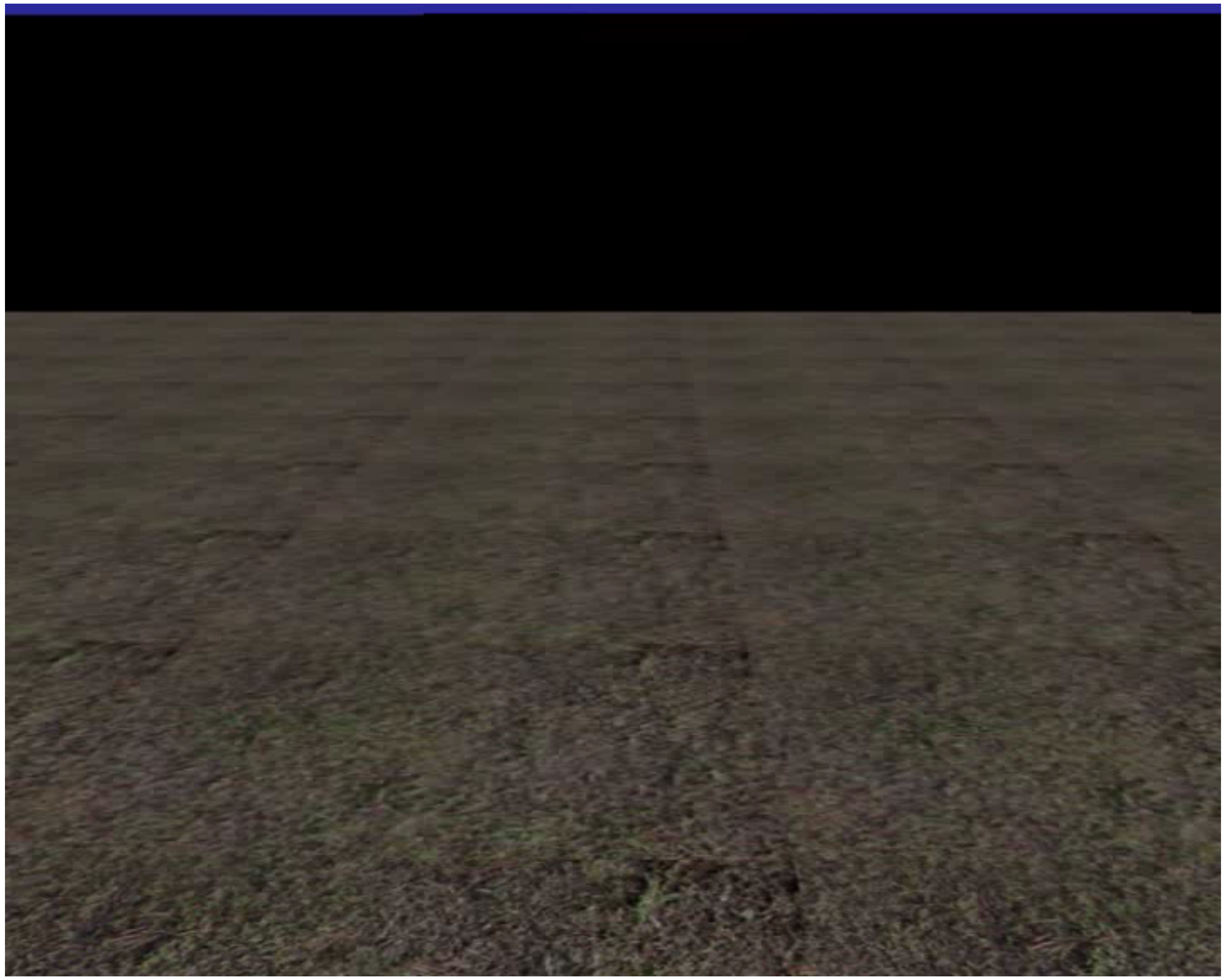


Jasmine robots

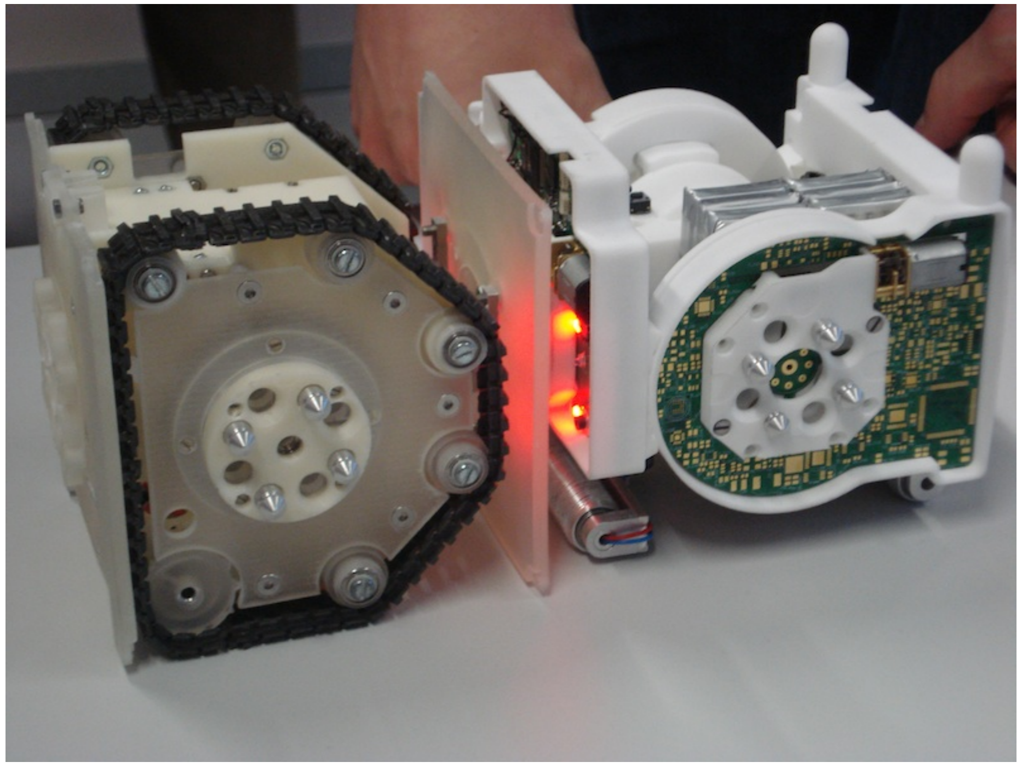


SEVENTH FRAMEWORK PROGRAMME

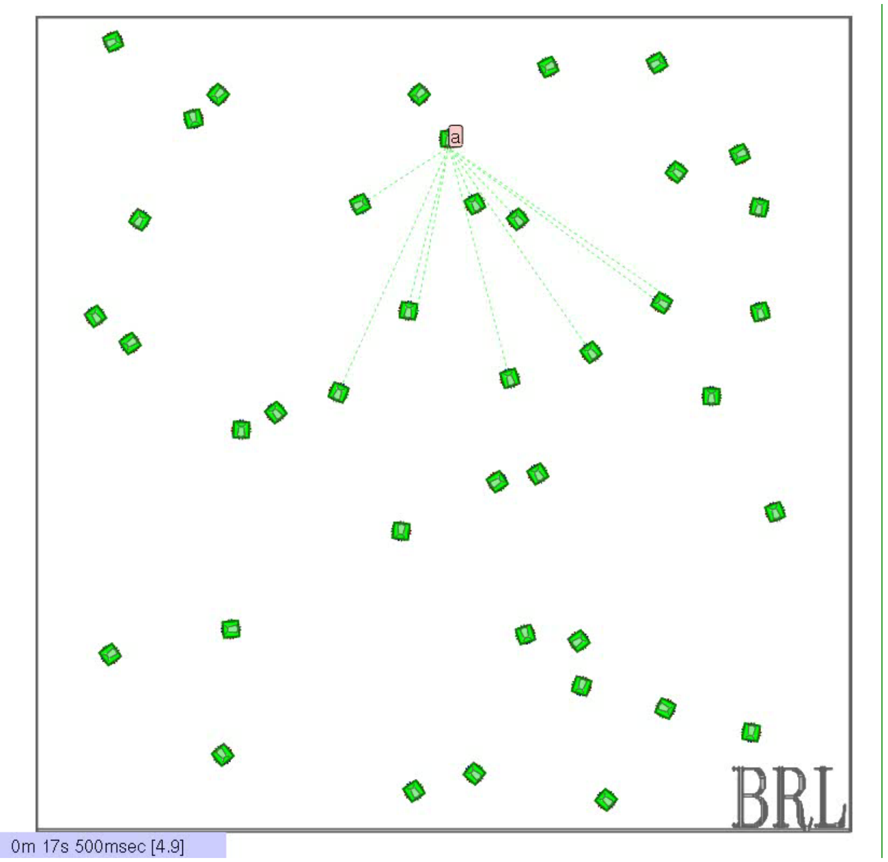
www.symbrion.eu



3D physics simulation of artificial organism (Karlsruhe)



Symbrion robots - April 2010



Development of swarm to organism
2D morphogenesis (BRL)

The Emergence of Artificial Culture in Robot Societies

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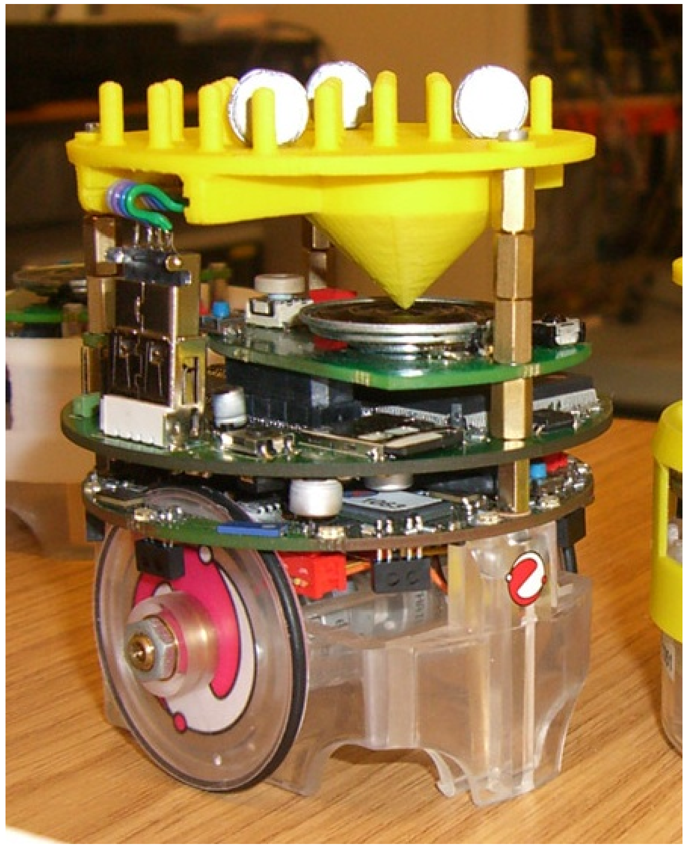
Social learning in collective robotics

- our aim is to model the *processes* and *mechanisms* of the emergence of culture in social agents...
- by introducing robot-robot imitation (social learning) to model and study the propagation of robot *memes* across the robot society



e-Puck robots

Artificial Culture Lab

http://sites.google.com/site/artcultproject/

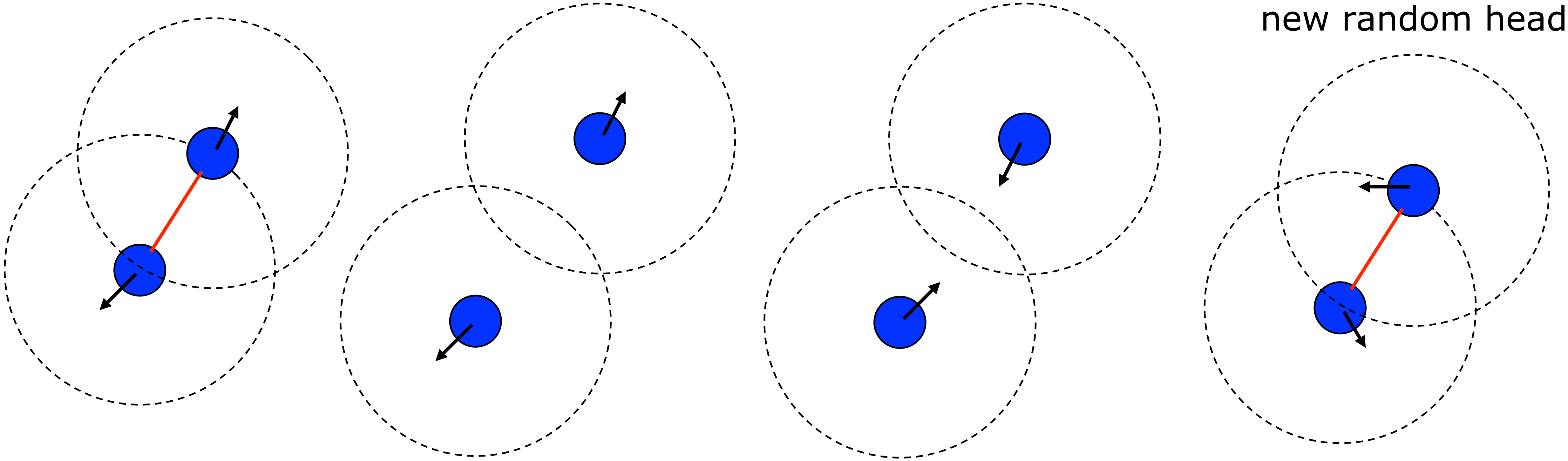
A minimalist wireless connected swarm

- Research question: is it possible to maintain swarm integrity (aggregation) using wireless alone?
- In other words:
  - Is it possible to use wireless connectivity as a *structural component* in building swarm systems..?
- We seek simple rules linking locomotion with communications
  - To create emergent swarm coherence and
  - Scalable control of swarm morphology

A Minimalist Approach

- Robots have
  - Range limited, omni-directional wireless communications
    - *Situated communications*
    - Robots can transmit their identity, but signal strength not available
  - No global positional information
  - No range or bearing sensors
  - Only local knowledge of connectivity

Primitive behaviour

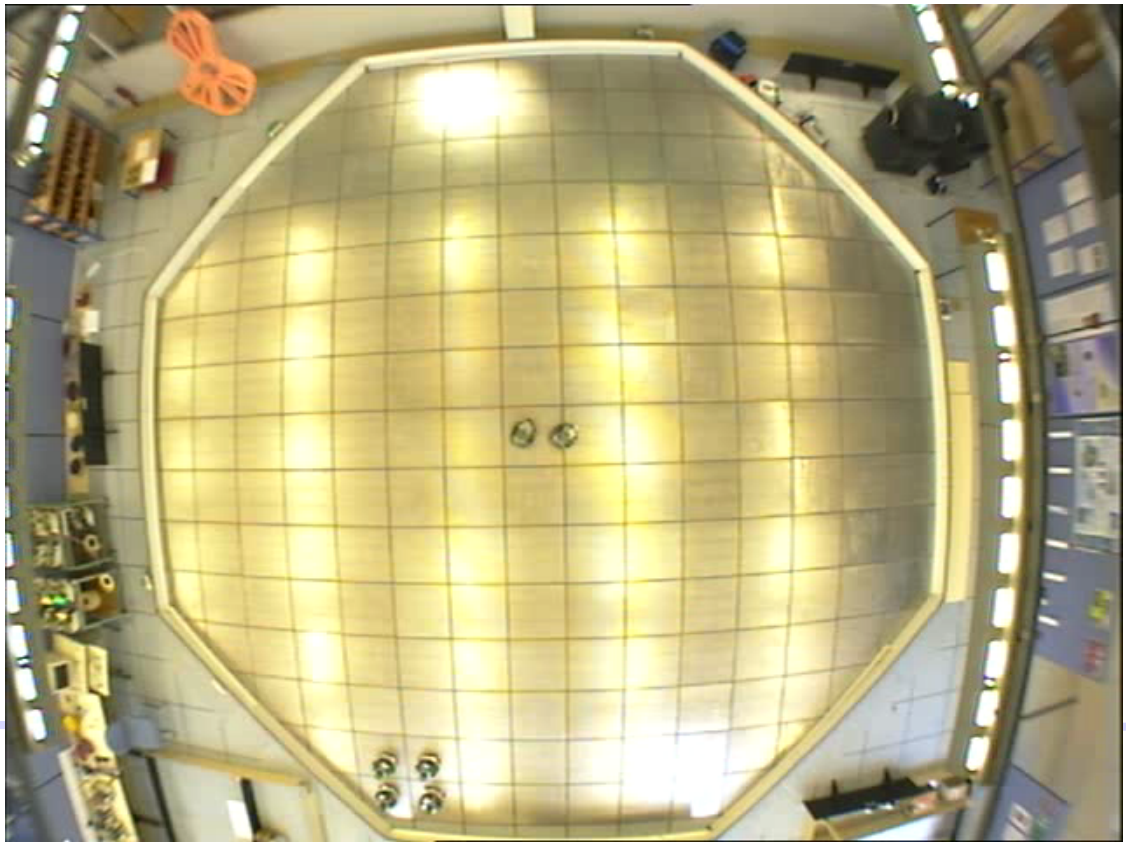


(i) Connected

(ii) Connection lost

(iii) Turn back

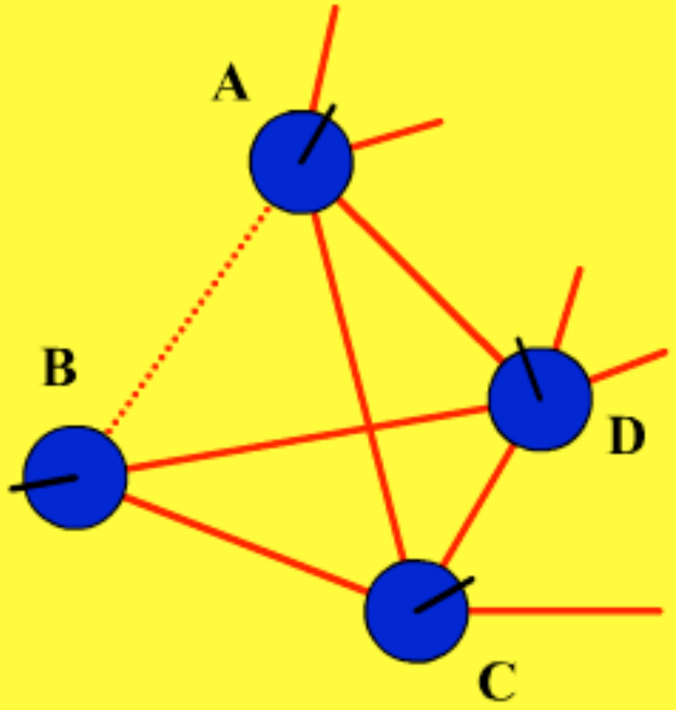
(iv) Reconnected, choose new random heading



Primitive behaviour running on 2 Linuxbots

Basic Algorithm

- Extend the basic primitive to multiple robots…
  - React to the number of neighbours in range, i.e. the number of connections K



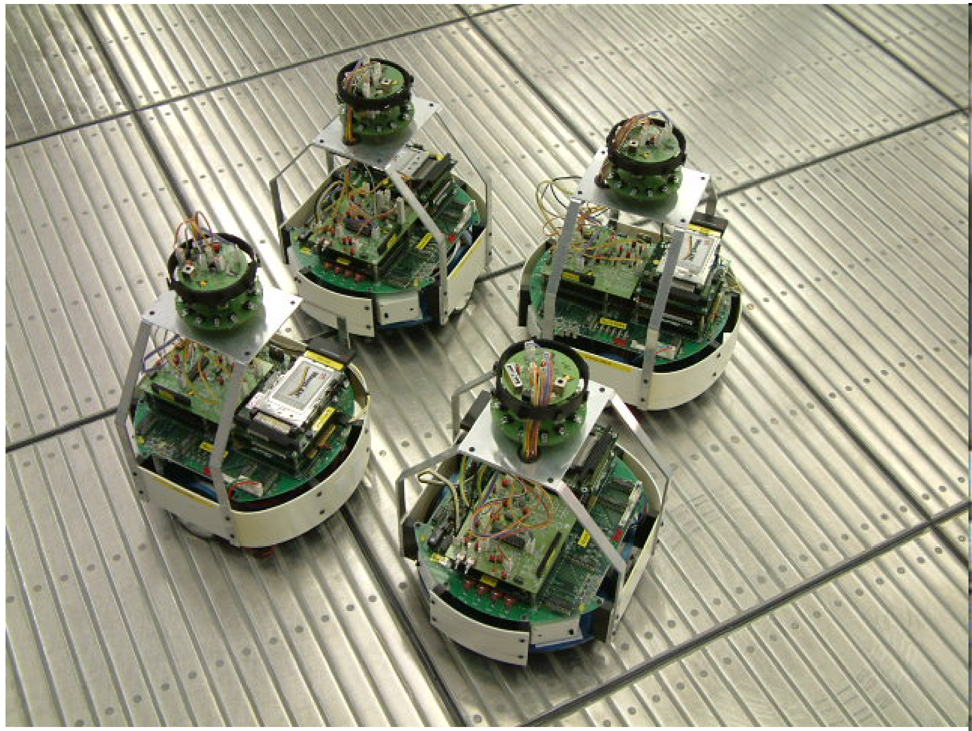
$K(A) = 4$

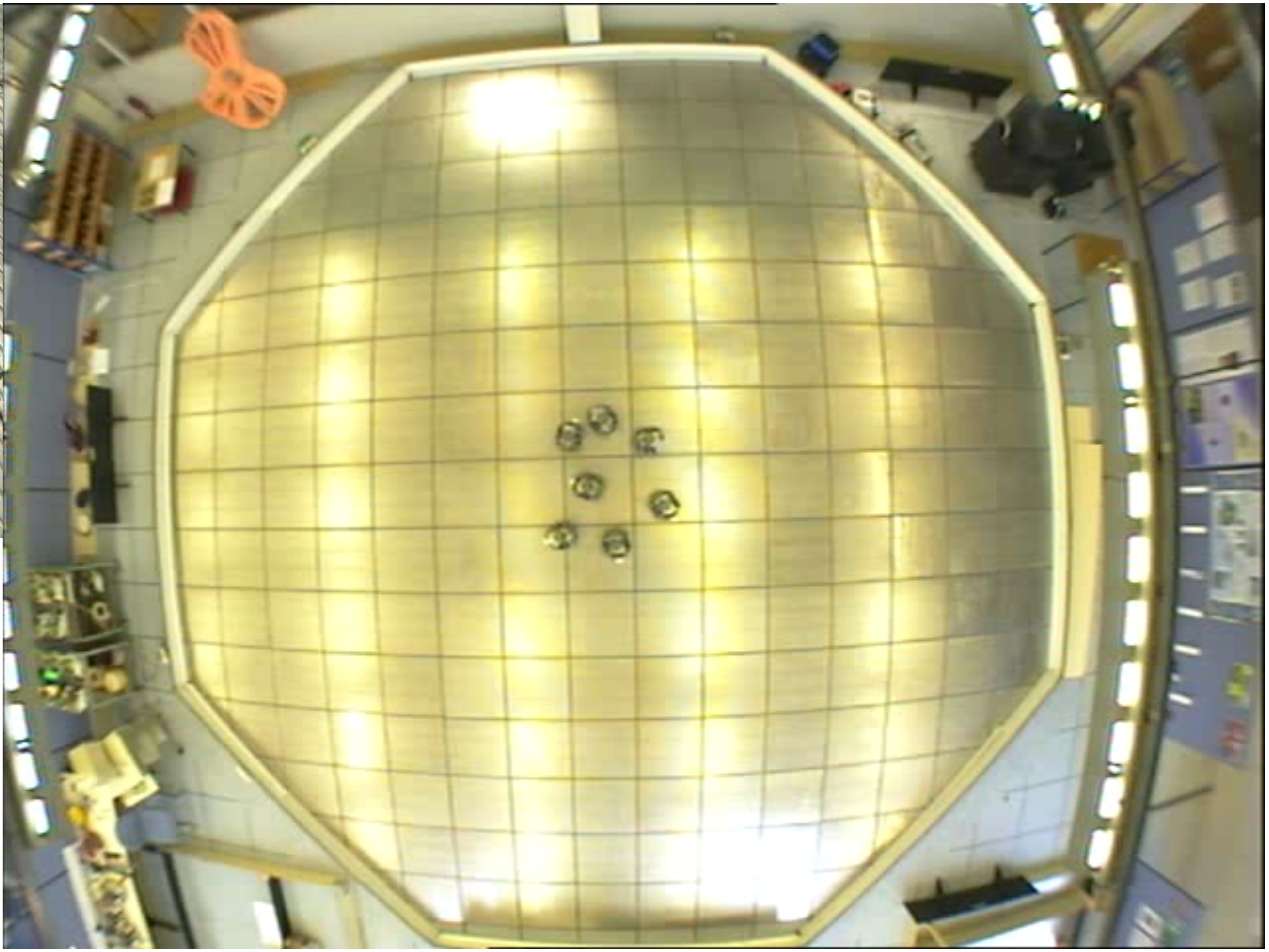
$K(B) = 2$

rule : *if ($K <$ Alpha) turn 180 degrees*

Physical Implementation

- Experimental platform: the LinuxBot*

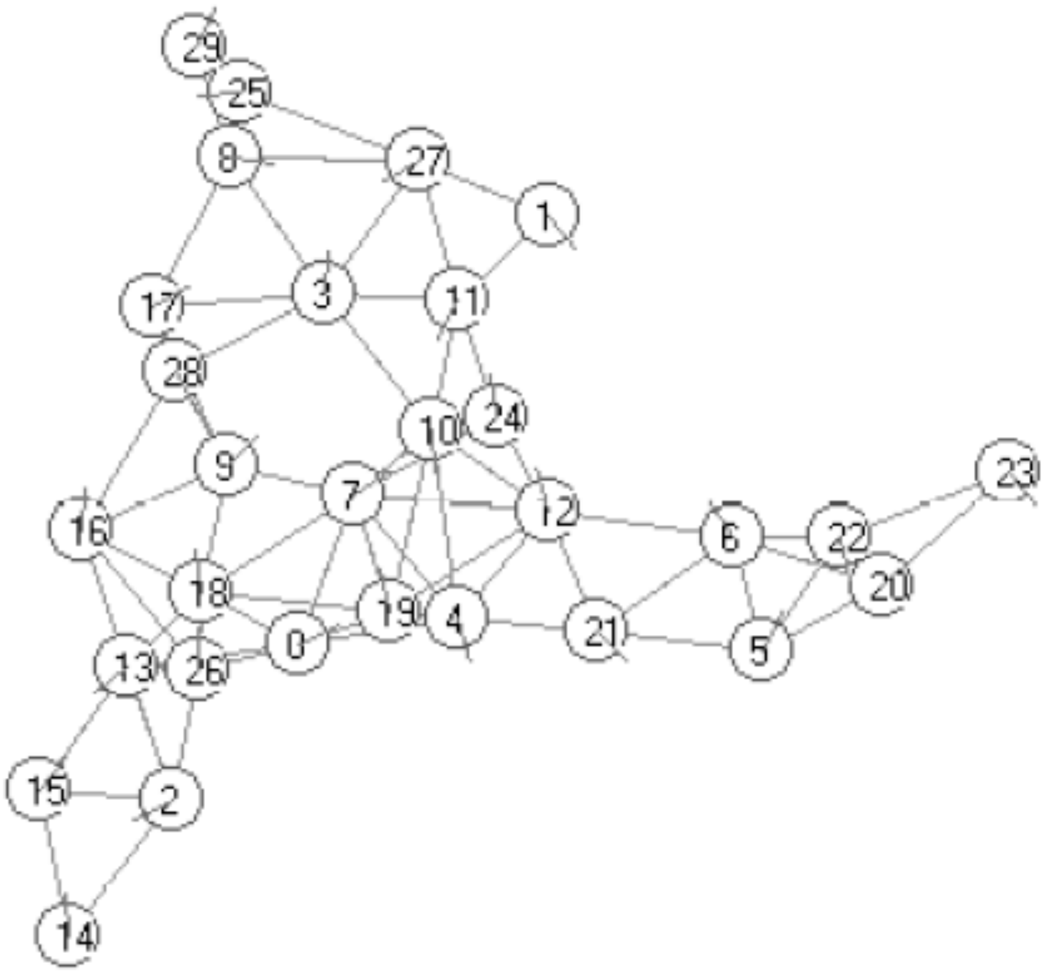


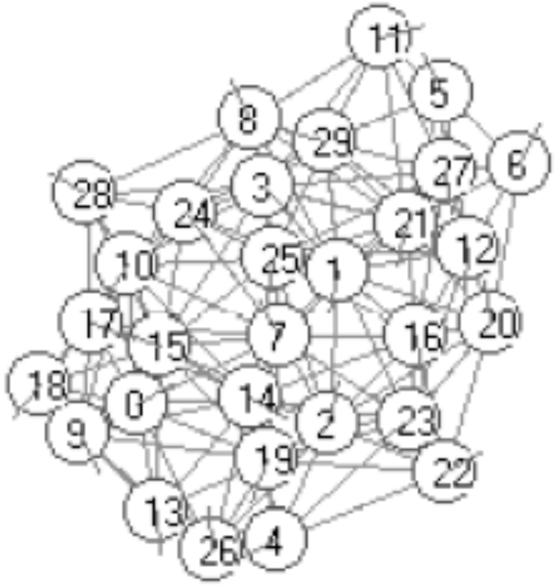


*See: Winfield & Holland, Microprocessors & Microsystems 23(10), 2000.

Emergent ad-hoc wirelessly connected network

- Single parameter area control:
  - swarm disposition for α = 5, α = 10



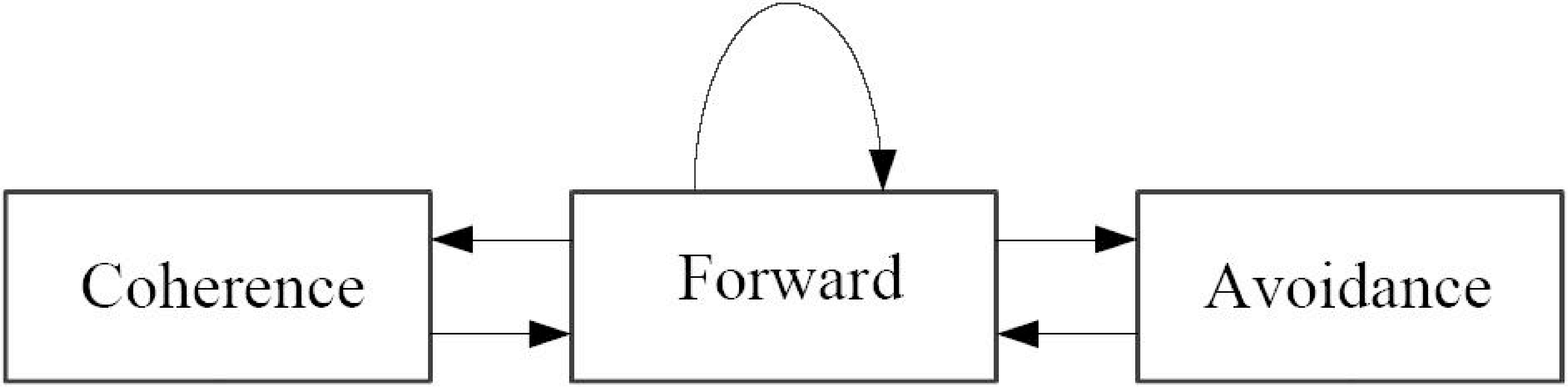


Mathematical Modelling

- We model the wireless connected swarm, by extending the probabilistic approach of Martinoli *et al**.
- We take the Finite State Machine (FSM)
  - express as an ensemble of probabilistic FSMs...which lead to a set of difference equations
  - geometrically estimate the transition probabilities
  - compare the model with experimental data

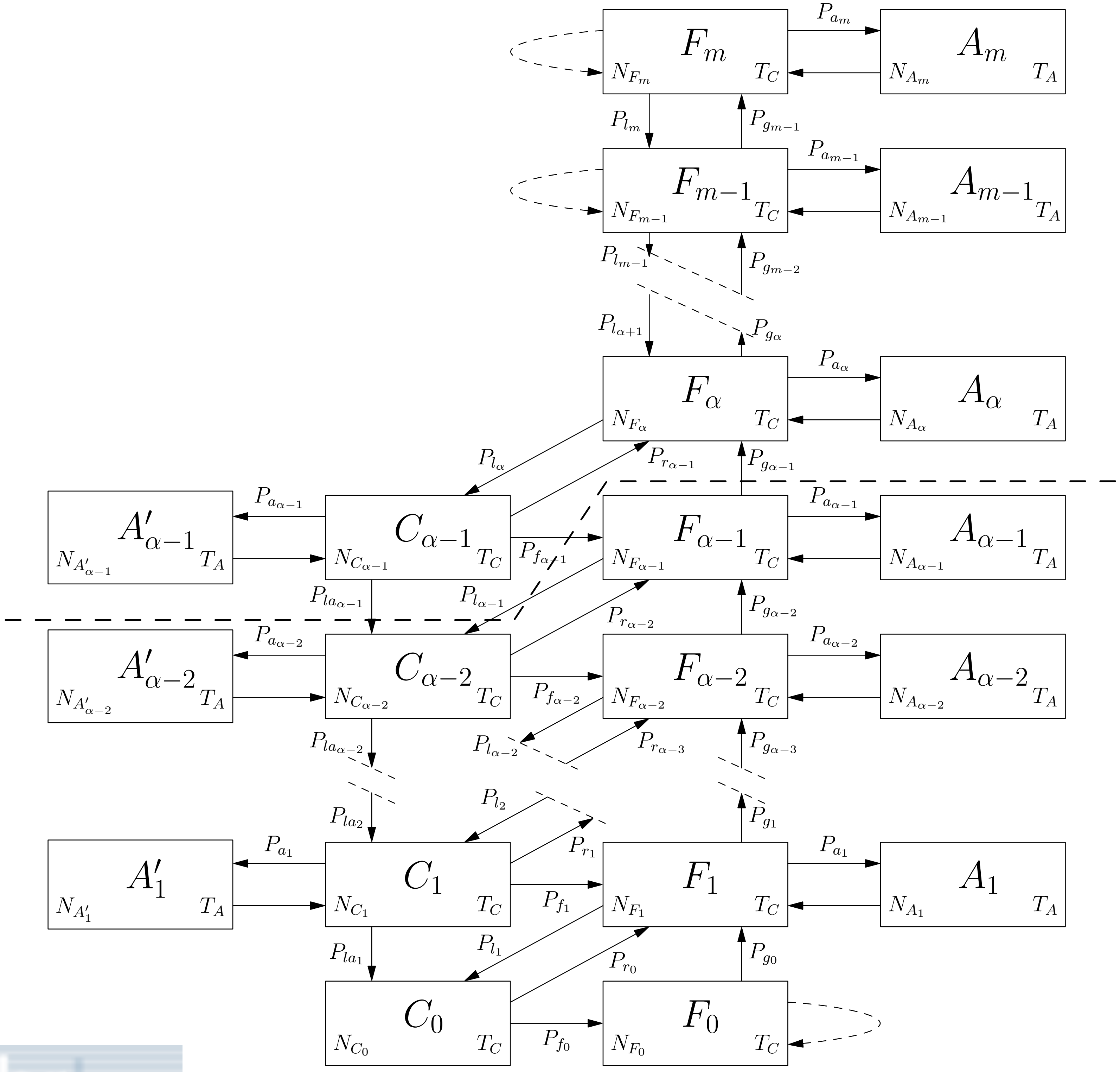
*See e.g. Martinoli, Easton and Agassounon, IJRR 23(4), 2004

Simplified Finite State Machine



- Avoidance behaviour: triggered by short-range collision sensor
- Coherence behaviour: triggered by number of wireless connections falling below the threshold α

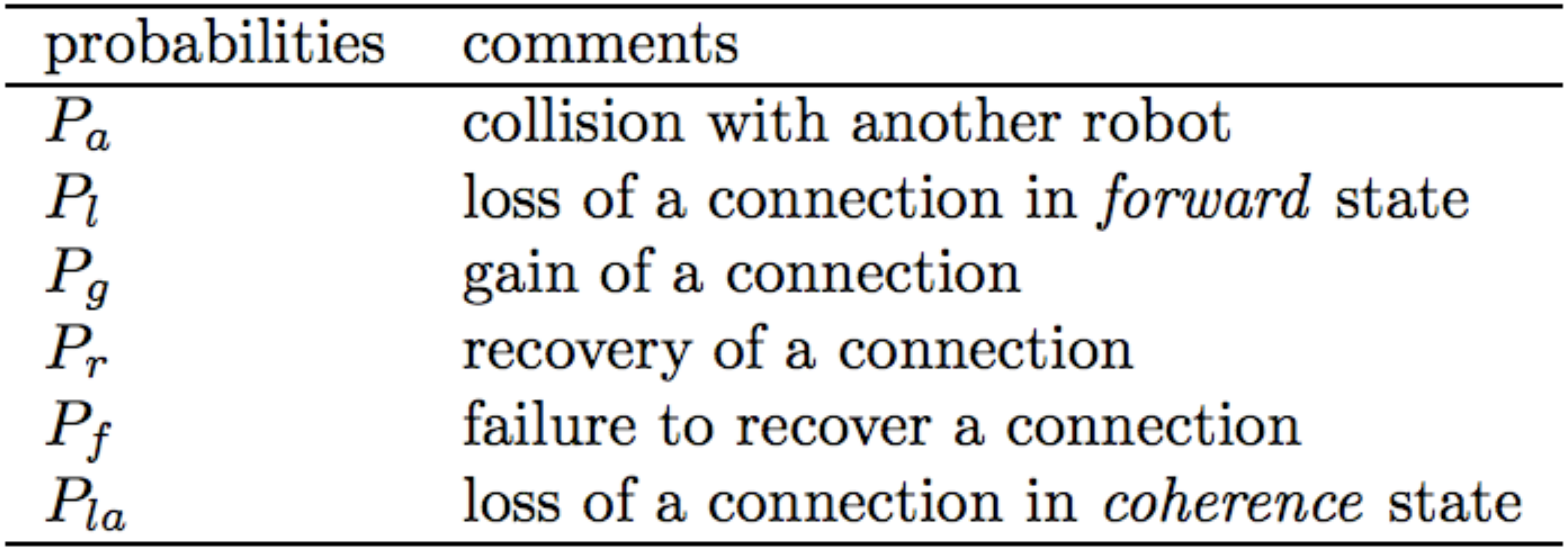
Probabilistic PFSM



Each box represents the number of robots in the swarm:
- *in a given state*, and
- *with a given number of connections*

The PFSM thus describes the state/ connection structure of the swarm.

Transition Probabilities



probabilities	comments
P_a	collision with another robot
P_l	loss of a connection in *forward* state
P_g	gain of a connection
P_r	recovery of a connection
P_f	failure to recover a connection
P_{la}	loss of a connection in *coherence* state

Difference Equations

- We can now write expressions for the change in number of robots in each state from one time step to the next
  - for the *avoidance* state

$$N_{A_i}(k+1) = N_{A_i}(k) + P_{a_i} N_{F_i}(k) - \Delta_{A_i}(k+1-T_A)$$

$$\Delta_{A_i}(K+1) = P_{a_i} \Delta_{F_i}(k+1-T_A)$$

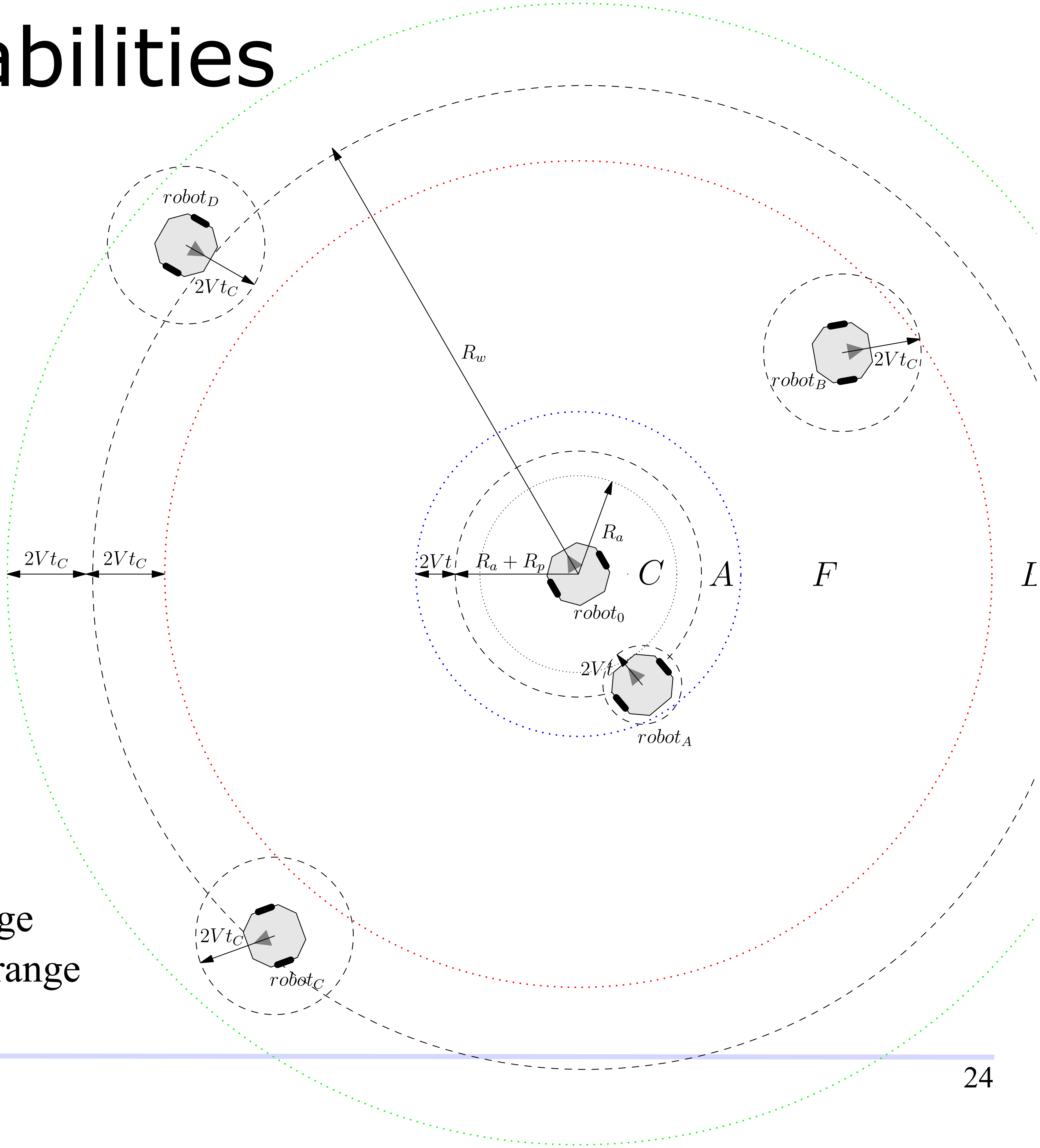
  - and so on for other states

- There are N robots in the swarm, so

$$N = \sum_{i=1}^{\alpha-1} N_{A'_i}(k) + \sum_{i=1}^{m} N_{A_i}(k) + \sum_{i=0}^{m} N_{F_i}(k) + \sum_{i=0}^{\alpha-1} N_{C_i}(k)$$

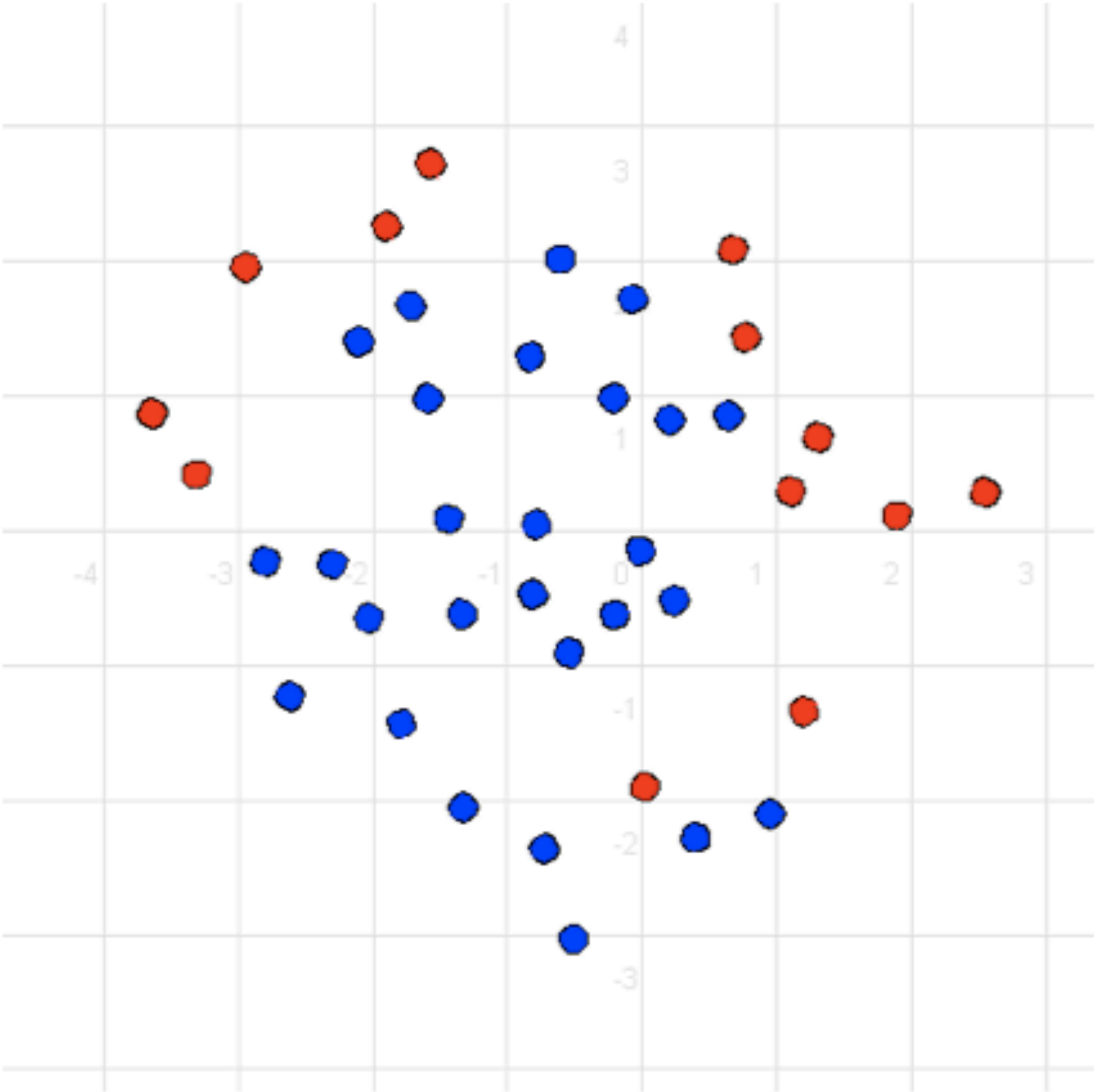
Geometrical estimation of transition probabilities

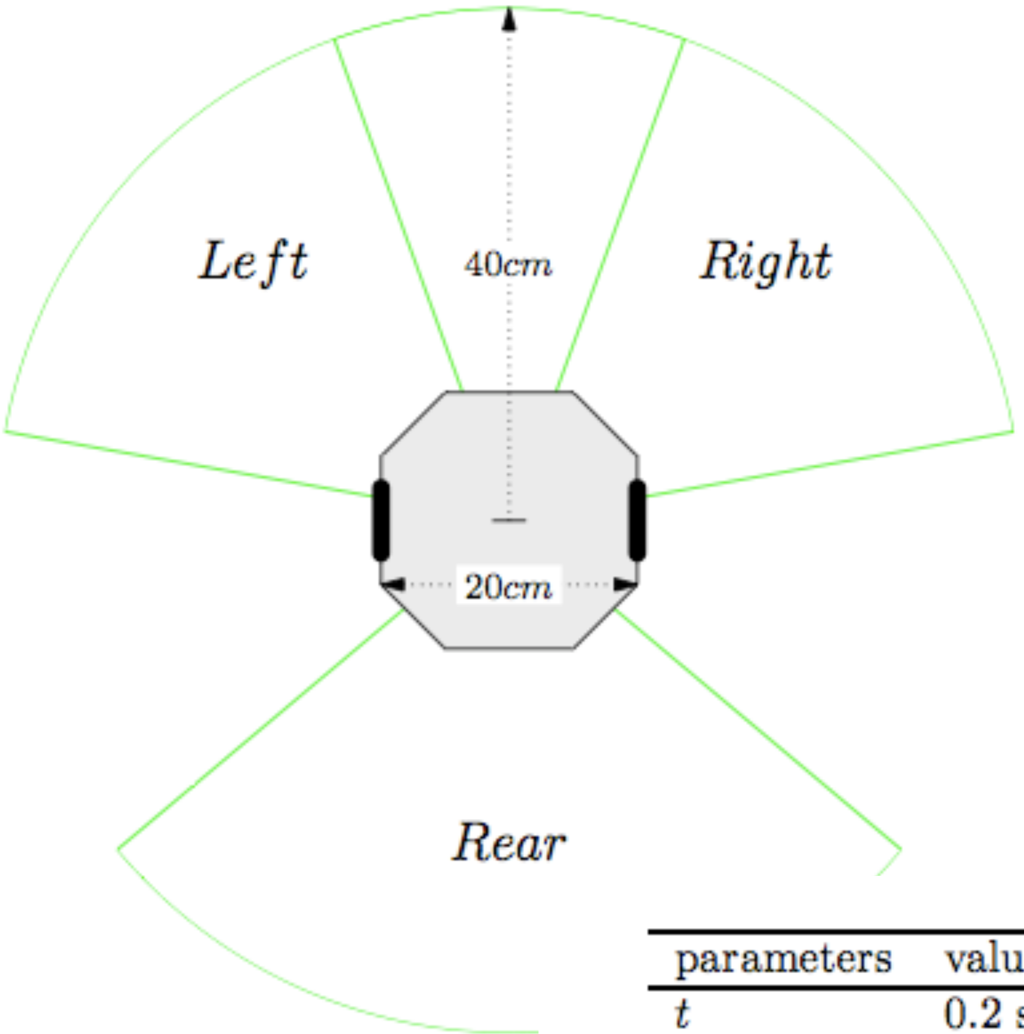
- With respect to $robot_o$
  - Region *C*: potential collision
  - Region *A*: potential avoidance
  - Region *L*: potential connection loss
  - Region *R*: potential connection recovery



R_a = avoidance sensor range
R_w = wireless connection range
V = robot velocity

Simulation for model validation





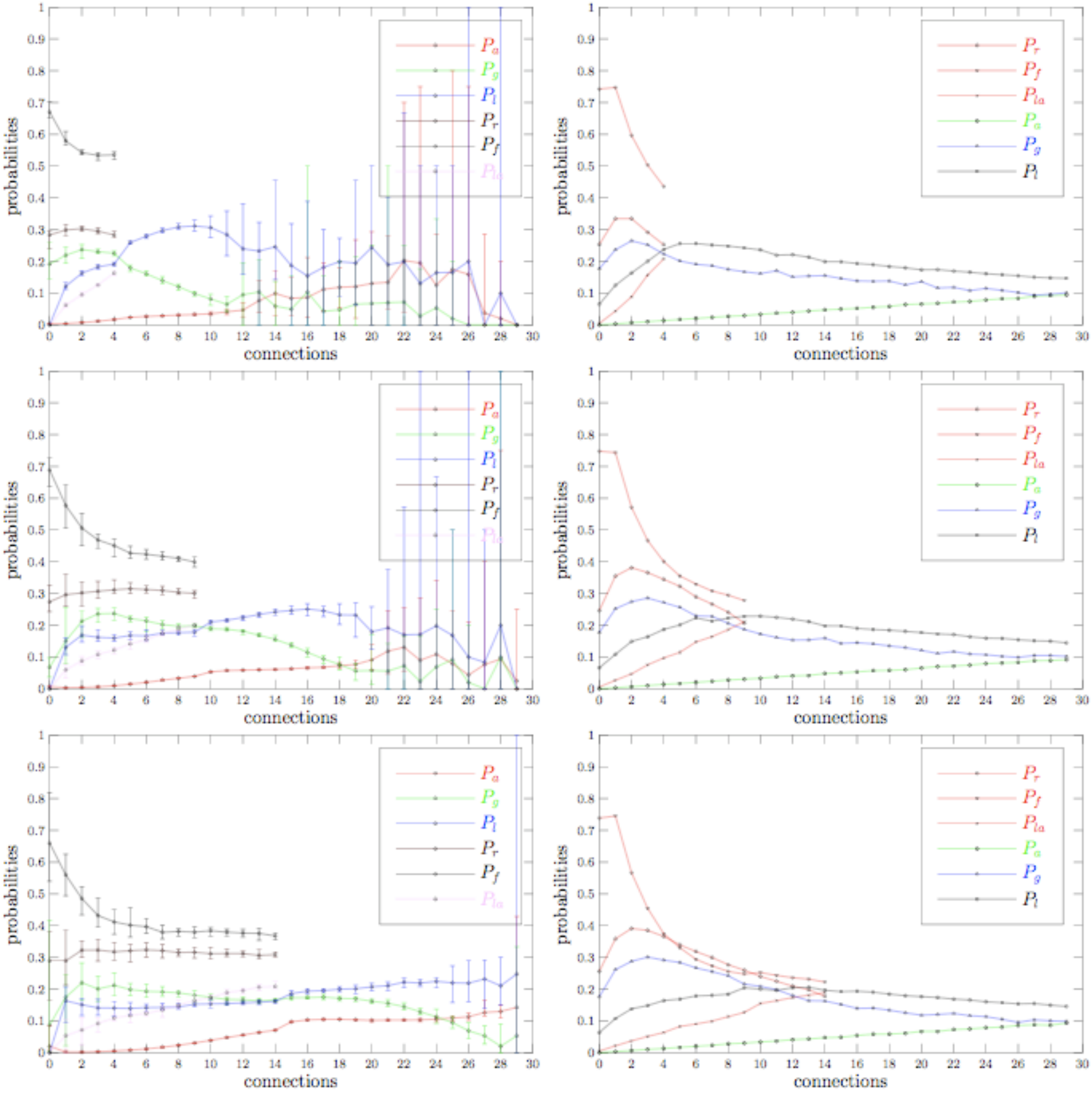
parameters	values
t	0.2 sec
t_C	3 sec
V	0.15 m/sec
R_a	0.4 m
R_p	0.1 m
R_w	2.0 m

Blue robots in *forward* state
Red robots in *coherence* state
screenshot from Player/Stage

State transition probabilities plotted against connectivity

Left: measured
Right: estimated

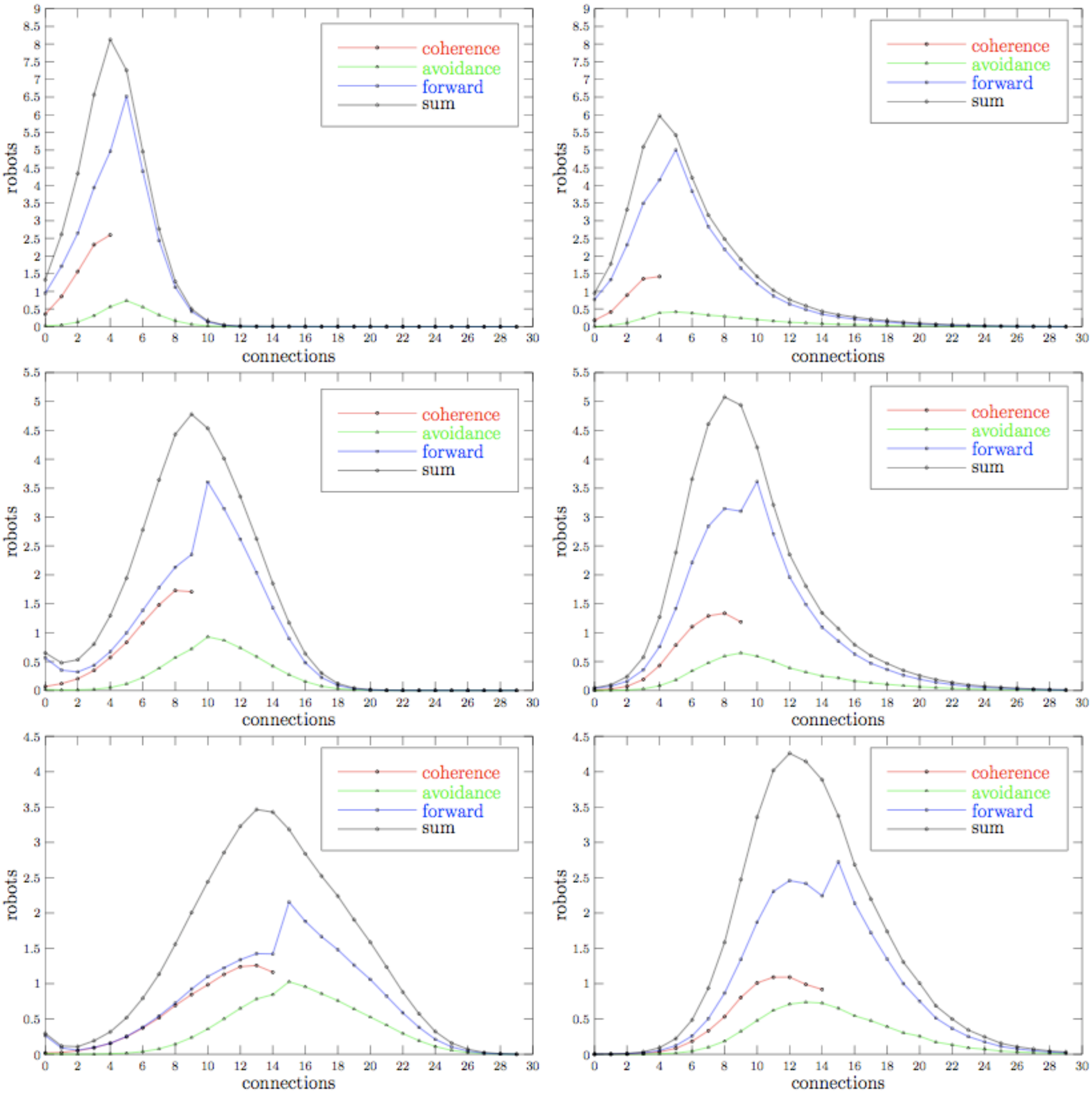
Top: α=5
middle: α=10
bottom: α=15



Connectivity: number of robots in states *coherence*, *avoidance* and *forward*

Left: measured
Right: modelled

Top: α=5
middle: α=10
bottom: α=15



Discussion

- We have made a number of simplifying assumptions, primarily
  - in the PFSM we assume connections are lost or gained one-at-a-time
    - in practice more than one connection could be lost or gained in the time T_c between connectivity updates
  - we assume robots uniformly distributed
  - we assume linear functions for $A(x)$, $F(x)$ and $C(x)$
- Despite these assumptions the model achieves excellent qualitative and reasonable quantitative performance

Using Temporal Logic to Specify Emergent Behaviours

- We now investigate the use of a Linear Time Temporal Logic to specify (and possibly prove) emergent properties
- NASA have explored formal methods within the Autonomous Nano-Technology (ANTS) project
    - (Rouff et al, 2004)
    - however that work did not investigate a *temporal logic*

A linear time Temporal Logic

- Extends classical logic with temporal operators,
  - $\bigcirc\varphi$ is satisfied if φ is true in the *next* moment in time
  - $\Diamond\varphi$ is satisfied if φ is true at *some* future moment in time
  - $\Box\varphi$ is satisfied if φ is true at *all* future moments in time
- Concurrency modelled by interleaving

Specify primitive robot behaviours

Specify the movement primitives, bottom-up

$$moveN(i) := (\bigcirc x_i = x_i) \wedge (\bigcirc y_i = y_i + a)$$

$$\begin{aligned} &turn180Move(i) := \\ &\quad (\theta_i = S) \wedge (\bigcirc \theta_i = N) \wedge moveN(i) \vee \\ &\quad (\theta_i = W) \wedge (\bigcirc \theta_i = E) \wedge moveE(i) \vee \\ &\quad (\theta_i = N) \wedge (\bigcirc \theta_i = S) \wedge moveS(i) \vee \\ &\quad (\theta_i = E) \wedge (\bigcirc \theta_i = W) \wedge moveW(i) \end{aligned}$$

One of the four possible state/movement transitions

$$\begin{aligned} &forwardNotConnected(i) := \\ &\ (motion_i = forward) \wedge \neg connected(i) \wedge \\ &\ (\bigcirc motion_i = coherent) \wedge turn180Move(i) \end{aligned}$$

Overall swarm specification

Each robot must satisfy both Safety and Liveness properties at all future times

$$Robot_i := \Box(Safety_i \wedge Liveness_i)$$

Then specify the Swarm as the logical ‘and’ of all the robots

$$\begin{aligned} &Swarm := \\ &\quad Robot_1 \wedge Robot_2 \wedge ... \wedge Robot_N \wedge \\ &\quad \Box(\pi_1 \oplus \pi_2 \oplus ...\pi_N) \end{aligned}$$

Ensure that only 1 robot taking action at a time

Specification of Emergent Properties

Each robot is always connected

$$property1 := \Box\Diamond(\forall i \in robotSet.\ connected(i))$$

Eventually each robot will be connected to at least *k* distinct others

$$\begin{aligned}
&property2 := \\
&\quad \Diamond\Box(\forall i \in robotSet. \\
&\qquad (\exists j_1 \in robotSet\{i\}.\ inRange(i, j_1) \wedge \\
&\qquad \exists j_2 \in robotSet\{i\}.\ inRange(i, j_2) \wedge \\
&\qquad ... \\
&\qquad \exists j_k \in robotSet\{i\}.\ inRange(i, j_k) \wedge \\
&\qquad distinct(j_1, j_2, ..., j_k)))
\end{aligned}$$

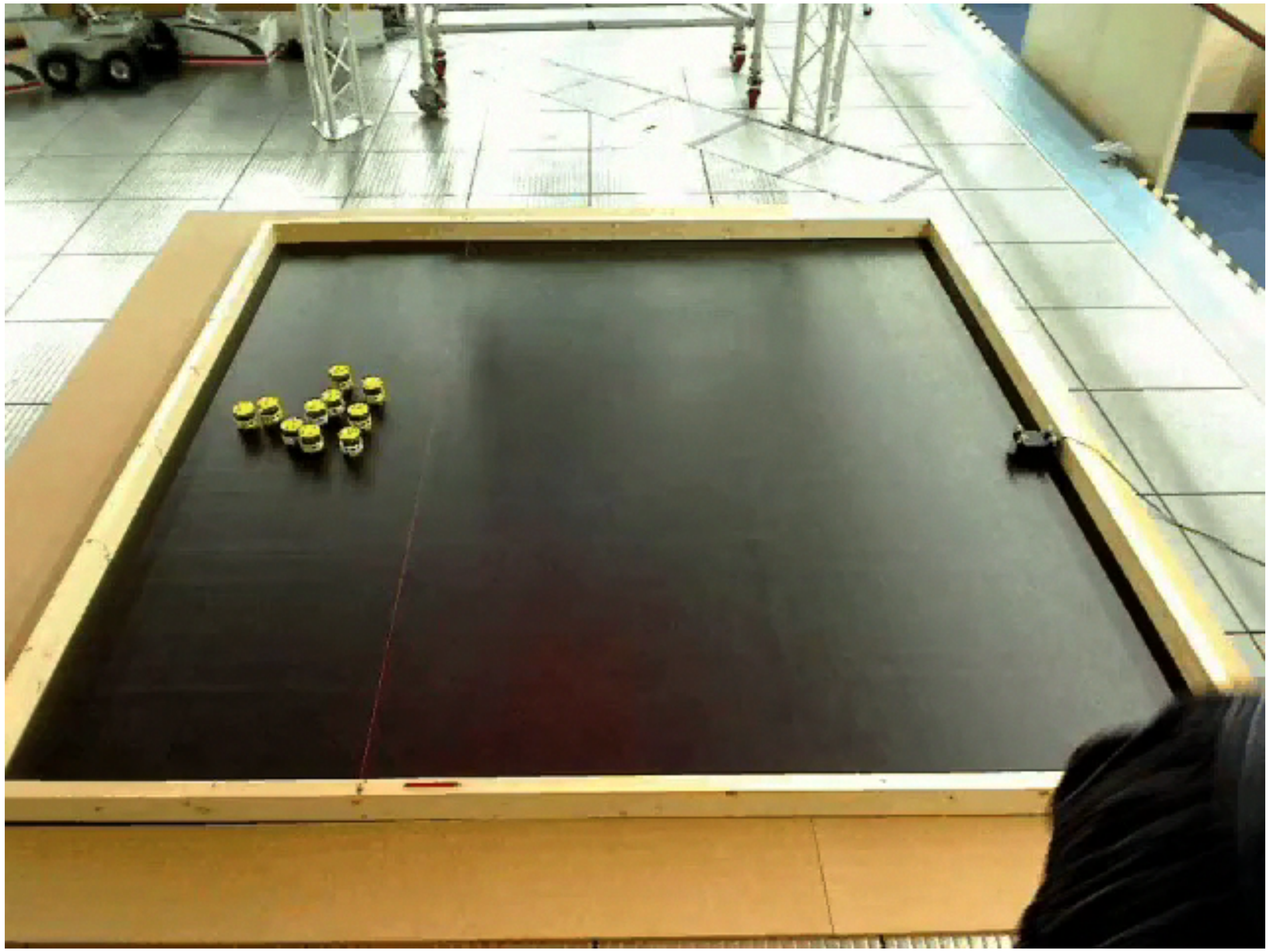
First specify the emergent properties

Now attempt to prove (or disprove) that the swarm of robots satisfies the emergent behaviours

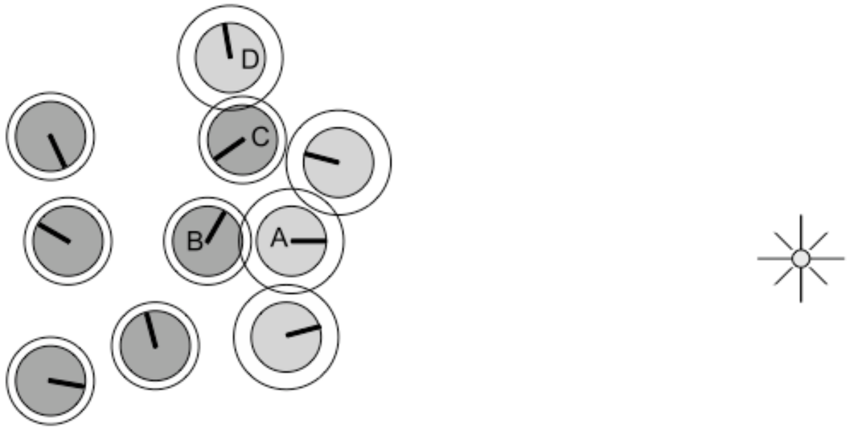
$$Swarm \Rightarrow property1$$

$$Swarm \Rightarrow property2$$

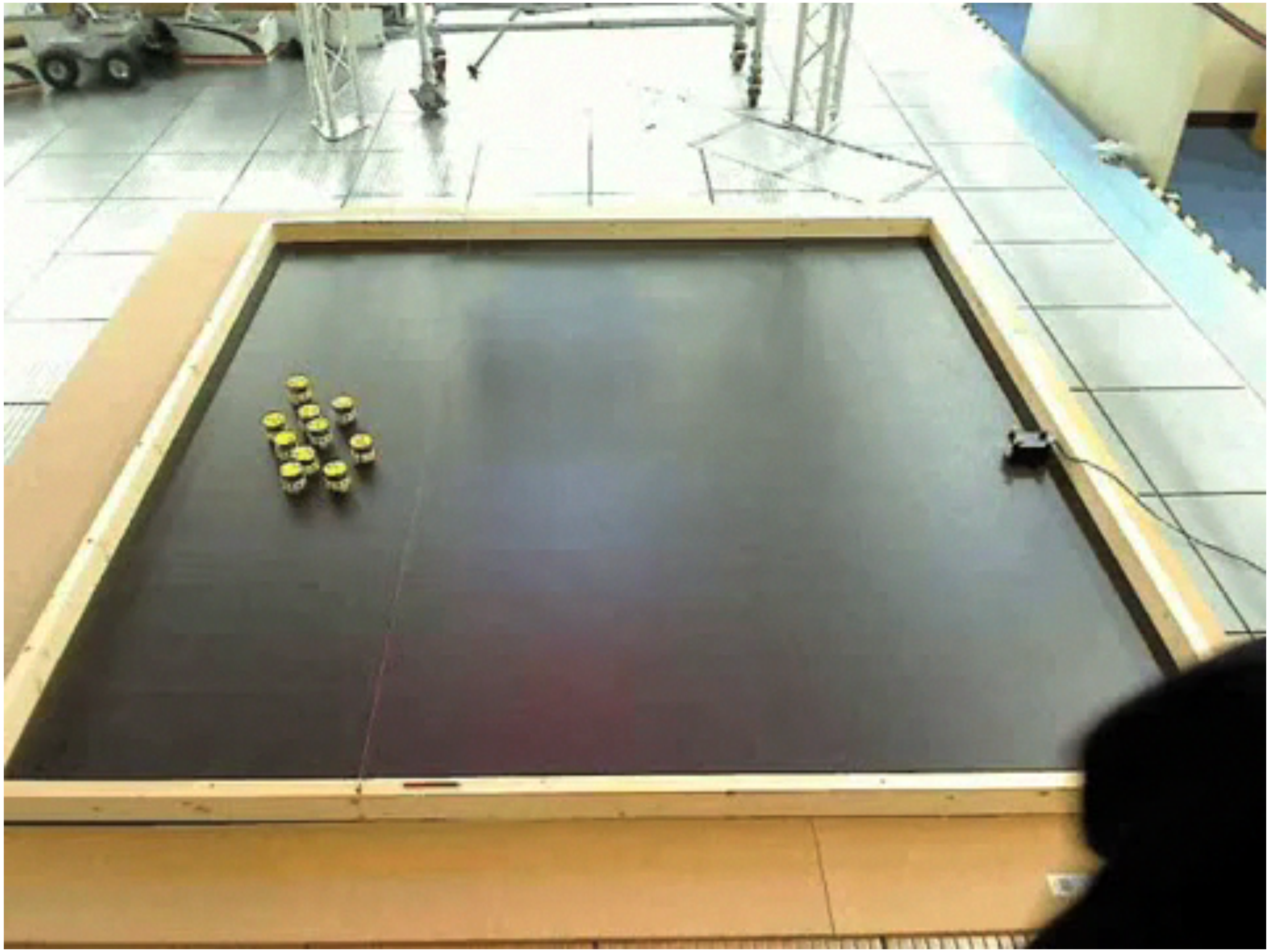
Reliability Modelling: emergent swarm taxis



- How does it work...
- Robots have simple aggregation:
  - short range: obstacle avoidance (repulsion)
  - longer range: maintain number of connected neighbours (attraction)
- Each robot also has a simple beacon sensor
  - symmetry breaking mechanism: *illuminated* robots have a slightly larger avoid radius than *occluded* robots



Swarm taxis with failures



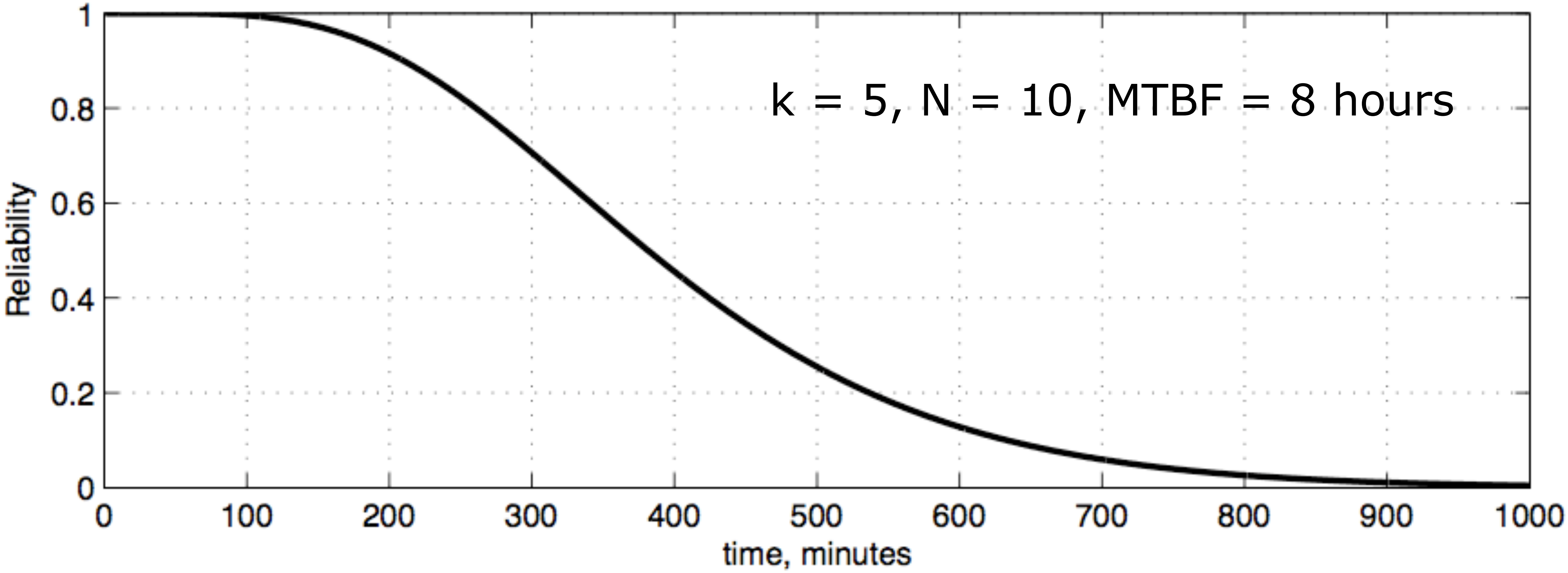
Bjerknes 2010

We then introduce worst-case *partial* failures - i.e. robots whose motors fail, but sensing and communications remains ok

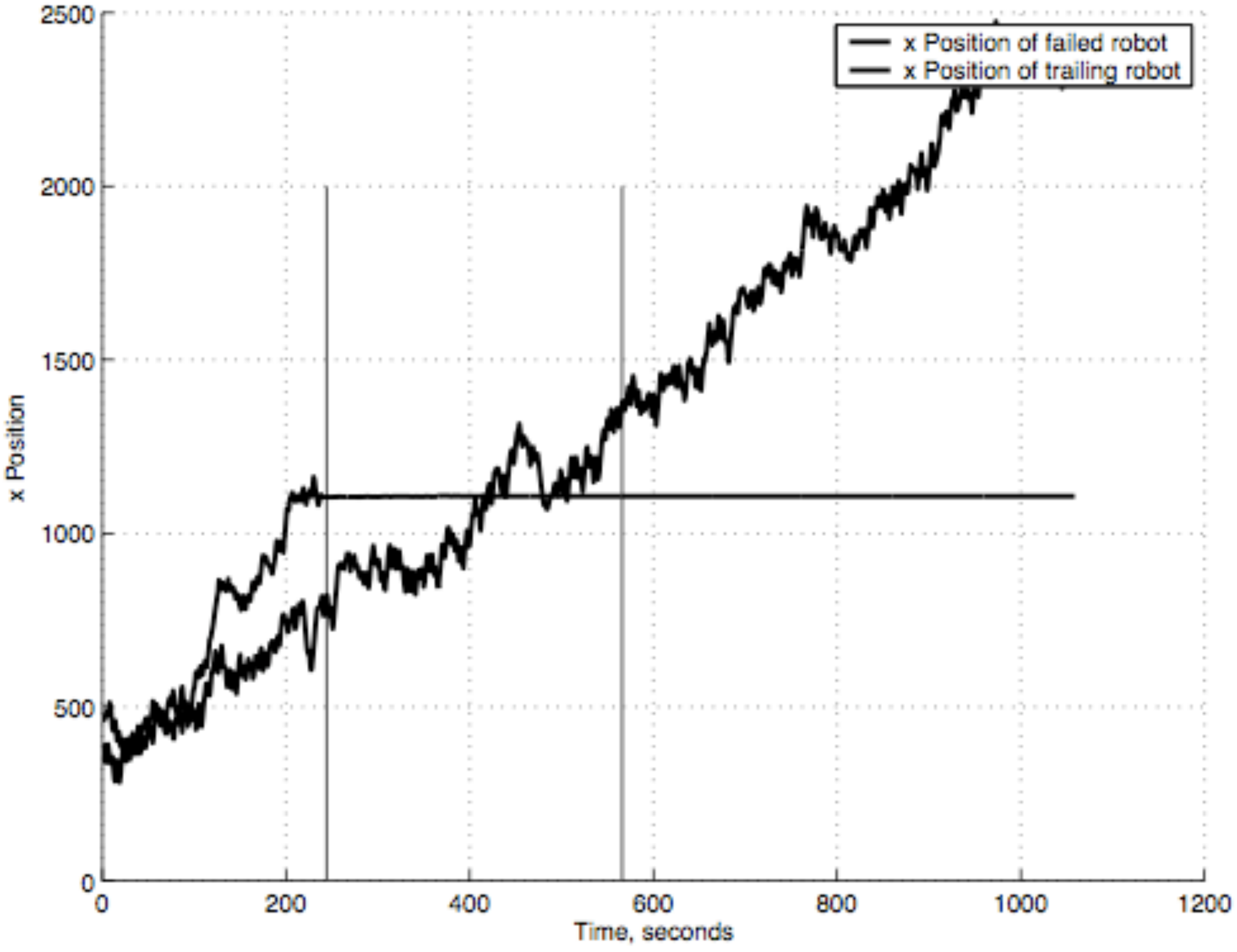
The k-out-of-N reliability model

The probability that at least k out of N robots are working at time t:

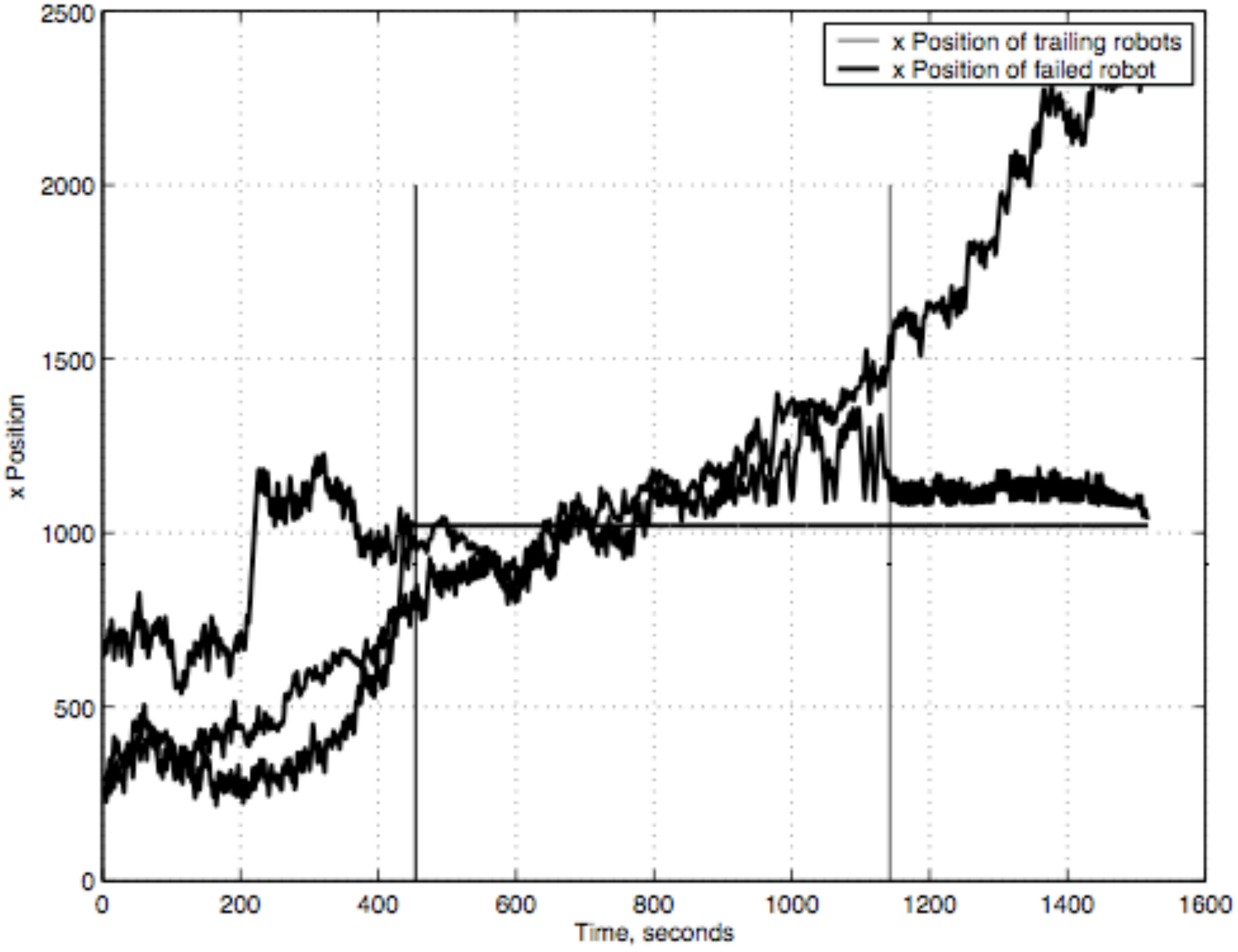
$$P(k,N,t) = \sum_{i=k}^{N} \binom{N}{i} (e^{-t\lambda})^{i} (1 - e^{-t\lambda})^{N-i} \qquad \lambda = \frac{1}{MTBF}$$



Swarm self-repair



Single robot complete failure H5



Single robot partial failure H1

Estimate k for partial failure H1

- Conservatively $k = 0.9N$
  - in other words, we believe the swarm can tolerate 10% of H1 failures at any one time (i.e. within swarm self-repair time)

Estimate swarm self-repair time

Since a robot can fail anywhere in the swarm the average distance the swarm needs to move to escape the failed robot is half the diameter of the swarm, i.e. $t = d/2v$, d = *swarm diameter*, v = *swarm velocity*

We know

$$v(N) = CN^{-\frac{1}{2}} \qquad \text{and} \qquad d(N) = D\sqrt{N}$$

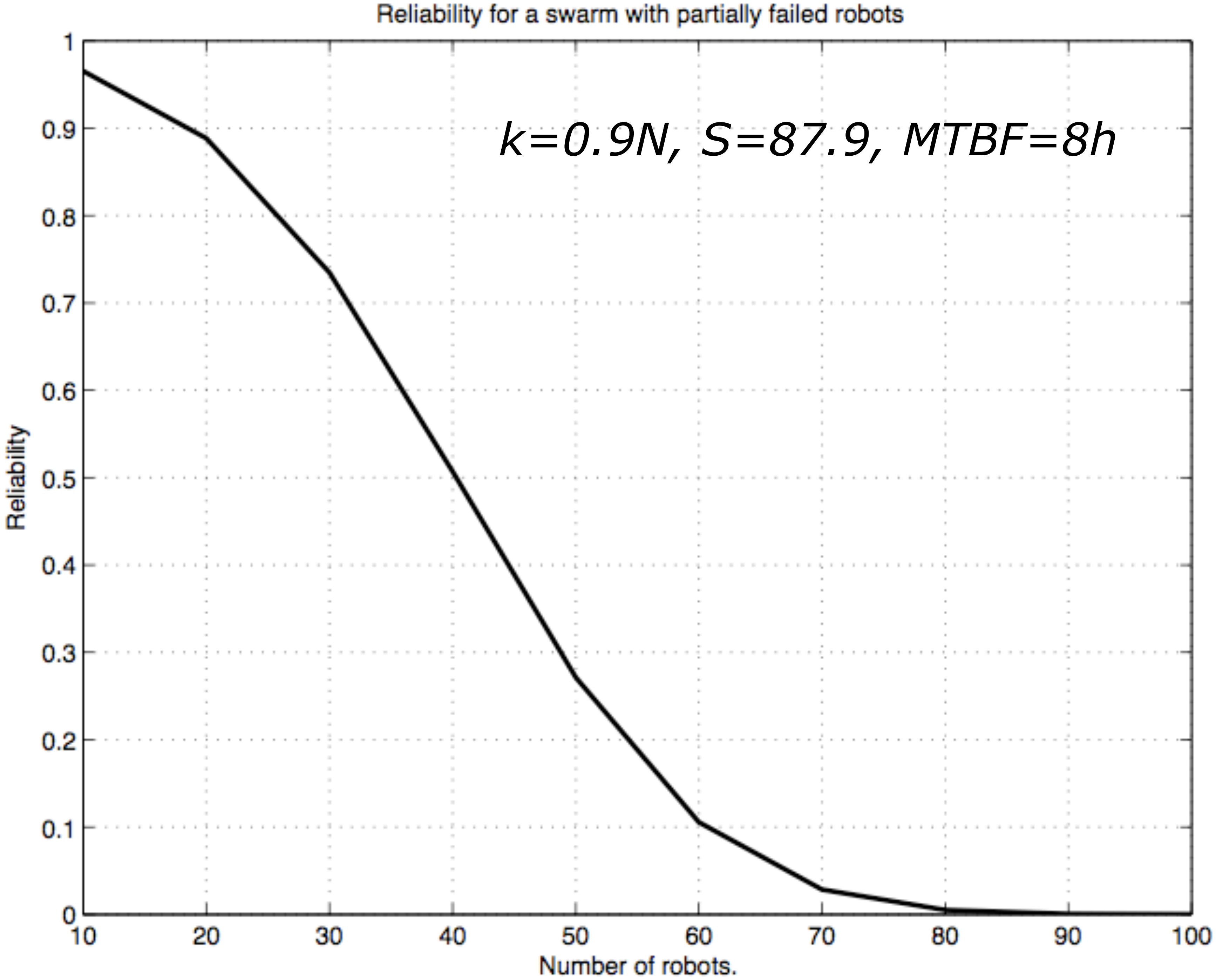
Thus

$$t(N) = \frac{D}{2C}N$$

Therefore swarm self repair time t is linear with N.

With $N=10$ and 1 partially failed robot mean swarm self repair time was measure as *870s*, thus the constant S = $D/2C = 87.9$

Reliability as a function of swarm size



Discussion

- The frequent assumption, that swarm systems are automatically scalable and robust, is seriously incorrect
- This result strongly suggests that scaling systems (which rely on emergence or self-organising mechanisms) requires more sophisticated internal mechanisms for dealing with worst-case failures:
  - an *immune system*

Thank you!

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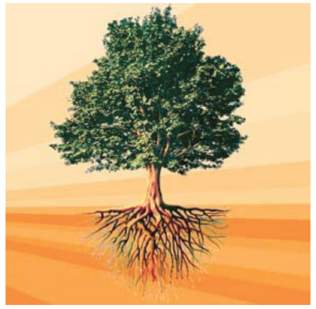

SEVENTH FRAMEWORK
PROGRAMME

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  - Prof Chris Melhuish, Dr Tony Pipe
- Relevant publications:

  - A. F. T. Winfield, C. J. Harper, and J. Nembrini. Towards dependable swarms and a new discipline of swarm engineering. In Erol Sahin and William Spears, editors, Swarm Robotics Workshop: State-of-the-art Survey, number 3342, pages 126–142, Berlin Heidelberg, 2005. Springer-Verlag.
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