Distributed Control in Network-based Systems: a complex systems approach

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About the ARC Centre for Complex Systems
- Theme is theory & modelling of complex, adaptive network-based systems without central control

2 of our 3 main research programs:
- Genetic Regulatory Networks
  - models of gene-based control of growth & structure in biology
- Air Traffic Control (ATC):
  - modelling & simulation infrastructure for investigating new ATC operational concepts
ACCS: size & participants

  - primarily from the Australian Research Council (ARC)
  - for cross-disciplinary basic research
- Based at UQ (Brisbane) with nodes at Monash (Melbourne), Aust Defence Force Academy (Canberra), Griffith (Brisbane)
- Inter-disciplinary team (80+ researchers, 40+ PhD students):
  - systems & software engineering
  - *Complex Systems Science* theorists
  - computational science, visualisation
  - data mining, machine learning
  - human factors
  - economics
  - bioinformatics

Distributed control in network-based systems
Holistic view vs reductionism
   - “The whole is greater than the sum of the parts”
Re-emerged in 1980’s from the “soft sciences” (biology, sociology, economics)
   - now very active: e.g. Santa Fe Institute, New England CSI
One branch seeks to understand how simple rules about interactions between components can generate complex behaviour
   - e.g. Flocking behaviour from 3 simple rules
Another branch studies networks and how their topology affects system properties: eg scale-free networks: function 

\[ \text{Nodes}(k) = \# \text{nodes with k neighbours} \] 

follows an inverse power law typically \( k^{-2.3} \)

- Internet backbone
- Metabolic reaction
- Telephone calls
- www
- Airline routes
Network degradation

From D Jarvis, *A methodology for analyzing complex military Command And Control (C2) networks*

- highly resistant to local failures
- highly vulnerable to attacks on hubs
The Centre’s research program

- Focus on theory and modelling of complex, adaptive network-based systems without centralised control
  - Investigate how complex system behaviours arise from simple agent behaviours & connections between agents
- Aim is to deliver theory, methods and tools for studying such systems
3 main application areas

- Genetic regulatory networks: how DNA controls growth & development of biological organisms
- “Free flight” air-traffic control: how to let airlines choose aircraft trajectories
- Evolutionary economic systems: how agents acting in networks (typically markets) lead to macro-economic behaviour

Plus “infrastructure” projects:
  - eg Dependability of Computer-based Systems
    - Modelling system requirements for complex systems
Outline of talk

- About the ARC Centre for Complex Systems
  - Theme is theory & modelling of complex, adaptive network-based systems without central control

2 of the 3 main research programs:

- **Genetic Regulatory Networks**
  - models of gene-based control of growth & structure in biology

- **Air Traffic Control**
  - modelling & simulation of new ATC operational concepts
Gene regulation: a dummy’s view

- As cells divide & DNA replicates, individual genes can get turned on (“get expressed”) or off
- Gene expression state determines cell type
- There are networks of particular genes that regulate gene expression
  - ie, control which genes get turned on & turned off in the next generation of cells, when cells divide
- Biologists are developing insights into the different forms of control used in nature

Distributed control in network-based systems
Gene Regulatory Network Modelling

DNA Sequence

Multiple processes from expression to development

Gene sequence

Gene expression

Network Interactions

Ontogeny, growth & form

I. Genome

..GTCATGCTATACCTGGGCTAT
CATGCTGCTACATCGTGTCT
TACCTGTATACCTTTACTGCT
TACCTGCTACATCGTGTCT
TACCTGCTACATCGTGTCT
TACCTGCTACATCGTGTCT
TACCTGCTACATCGTGTCT
TACCTGCTACATCGTGTCT
TACCTGCTACATCGTGTCT

Gene expression

Network Interactions

Ontogeny, growth & form
Modelling of organism ontogeny

- Ontogeny = cell type lineage (type & position)
- *C. elegans* nematode worm
  - 10 “generations” of cell divisions up till birth (600 cells)
  - 959 cells in adult worm
C. elegans first 5 cell divisions

Images from celdev.mov

Distributed control in network-based systems
Cell lineage tree for C. elegans
Discovering a GRN by fitting to data

Simulations by Nic Geard
L-systems (Lindenmayer): grammars for plant growth
   - elements include: stem segment (& length), bud, leaf branch (& angle), root segments, root nodules
   - production rules which include gene factors & signals
Root nodules in legumes

Model includes:
- GRN in root cells
- GRN in shoot cells
- signals between roots & shoots (Q, SDI)

Nodule formation occurs when bacteria present & SDI level low
Nodulation behaviour

Early Inoculation

Late Inoculation

NARK mutant

Distributed control in network-based systems
Outline of talk

- About the ARC Centre for Complex Systems
- Genetic Regulatory Networks
- Free Flight Air Traffic Control
  - or rather, freer flight = more user involvement
    - distribution of (some) control to aircrews/airlines
      - User Preferred Trajectories (UPTs)
  - Terminology, trends & challenges
  - ATC as a complex system
    - Multi Agent System models
    - Boids & flocking behaviour
  - 3 research projects modelling new ATC operational concepts
Air Traffic Control in the past(?)
Distributed control in network-based systems

ATC in Australia
An ATC sector at a quiet time
En-route flight phase: > 100km from airports

Different separation standards apply: eg
- Lateral: 5NM horizontal distance (~9km)
- Vertical: 1000’ (~300m)
- Longitudinal (aka “in trail”): 30NM when on same path
  ➢ 100NM when no radar

Separation violation: the separation standard is not met

Trajectory: 4D object, including route, height & time at waypoints
Changing nature of Air Traffic Management:
- Australian system now entirely computer-based
- ADSB will enable radar-like surveillance of whole continent
- improved navigation via GPS
  - routes no longer need to be fixed
  - “Flex tracks” enable taking advantage of tail winds
- Datalink communications will enable interchange of trajectory information

Goal: User Preferred Trajectories
- choose own route, height, speed
Advantages of UPTs

- Significant savings are possible if airlines can choose their own trajectories
  - eg fuel use, emissions, flight time
  - airlines can optimise to suit their own operational imperatives
    - fuel use, arrival time, manoeuvring, ...

- But UPTs is a major change in operational concept, with many research issues
  - 15 year lead time
  - 5 ConOps, 5 functional architecture, 5 test & prove
Airspace as a complex system

Emergent properties in this case are safety, efficiency, orderliness, predictability,…
Flocks of aircraft?

- One way to reduce controller workload would be to have aircraft fly in a cluster
  - “Moving sectors”
  - Aircraft do their own separation assurance within the cluster
  - Possible application of flocking behaviour?

- Flocking behaviour has been reduced to 3 simple rules:
3 simple steering behaviours

**Separation**: steer to avoid crowding local flockmates

**Alignment**: steer towards the average heading of local flockmates

**Cohesion**: steer to move toward the average position of local flockmates

*From Reynolds on Boids*
ATC Workload:

- With Airservices & UQ’s Human Factors Key Centre
- **Aim:** To develop a model that can:
  - Measure the flow of traffic through an air sector
  - Define a measure of traffic complexity ("workload")
  - Predict the level of workload that an average controller will experience
- The challenge: to model the effect of controller interventions on traffic
  - Also, controllers adapt their behaviour to moderate future workload
- Model will be used for inform design of new airspaces & for dynamic reconfiguration of airspaces
Ex 1: Medium workload, about to decrease
Ex 2: Medium workload, about to increase

Workload rating
Number of aircraft

Distributed control in network-based systems
Project 2: Moving sectors

- A methodology for training teams of agents
  - PhD project (KY Chen)
  - Problem is: how to discover the rules that agents should follow, so that they optimise their own objectives while simultaneously optimising overall team objectives
  - Case study 1: what trajectory should an aircraft fly, if it wants to join a moving sector
    - Assume all trajectories are published
  - Methodology is Learning Classifier Systems
    - Evolutionary rule learning
Project 3: trajectory-based ATM

- **Aim:** develop a more detailed concept of operations for trajectory-based ATM
  - …where UPTs are the default, & interventions are the exception

- **Key research questions:**
  - How to move from distance-based ATM to time-based trajectory management?
  - What is the appropriate functional architecture?
  - What real-time support can be provided to AOCs to produce trajectories that are safe & mutually optimal?
Summary & conclusions

ARC Centre for Complex Systems

- Focus is on network-based systems
- Simple agent behaviour + interactions = complex system behaviour
- 3 application areas: GRN, ATC, Evolutionary economic systems
- Methods & tools for understanding, managing & controlling complex systems
Genetic Regulatory Networks:

- 2 levels of agents:
  - genes with states *on/off* (gene expression)
  - Cells, with gene expression sets
- interactions (m:1):
  - send chemical signals to neighbouring cells
  - turn a gene on or off (regulate)
- System behaviour = ontogeny (cell lineage);
  development of growth & form
Air Traffic Control:

- agents = aircraft (/airlines) & ATCo’s
- agent behaviour = 4D trajectory
- interactions: avoid violating separation
- system behaviour = traffic complexity (workload)
Nature can give us inspirations

Modelling & simulation has many advantages over experimentation
  - But generally not possible to validate models quantitatively
  - Instead “validity” means: does it yield new insights
Acknowledgements

- Genetic Regulatory Networks program:
  - Janet Wiles – leader
  - Jim Hanan – plant models
  - Nic Geard – *C. elegans* models

- Air Traffic Control program:
  - ATC Workload project is a collaboration between ACCS, UQ’s Key Centre for Human Factors & Applied Cognitive Psychology & Airservices Australia
  - Andrew Neal, Project Leader
  - Penny Sanderson, Scott Boland, Ariel Liebman,…

- Plus many more