DEFENCE R&D DÉFENSE

Autonomy: 2010, 2020

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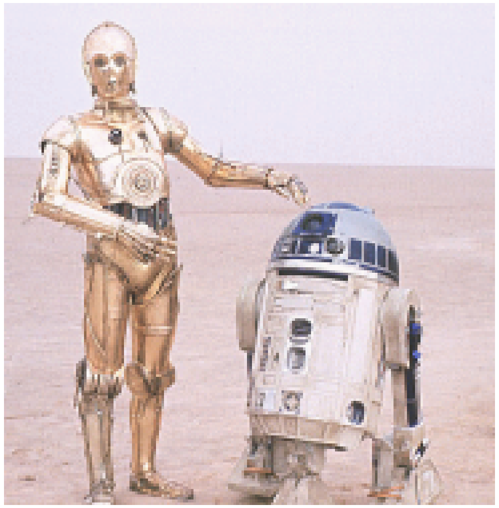
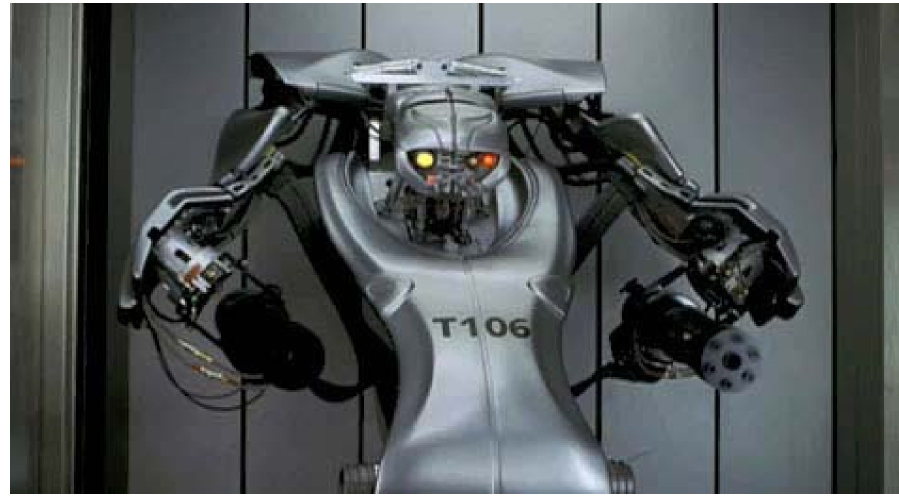
The future ?





The present

The problem

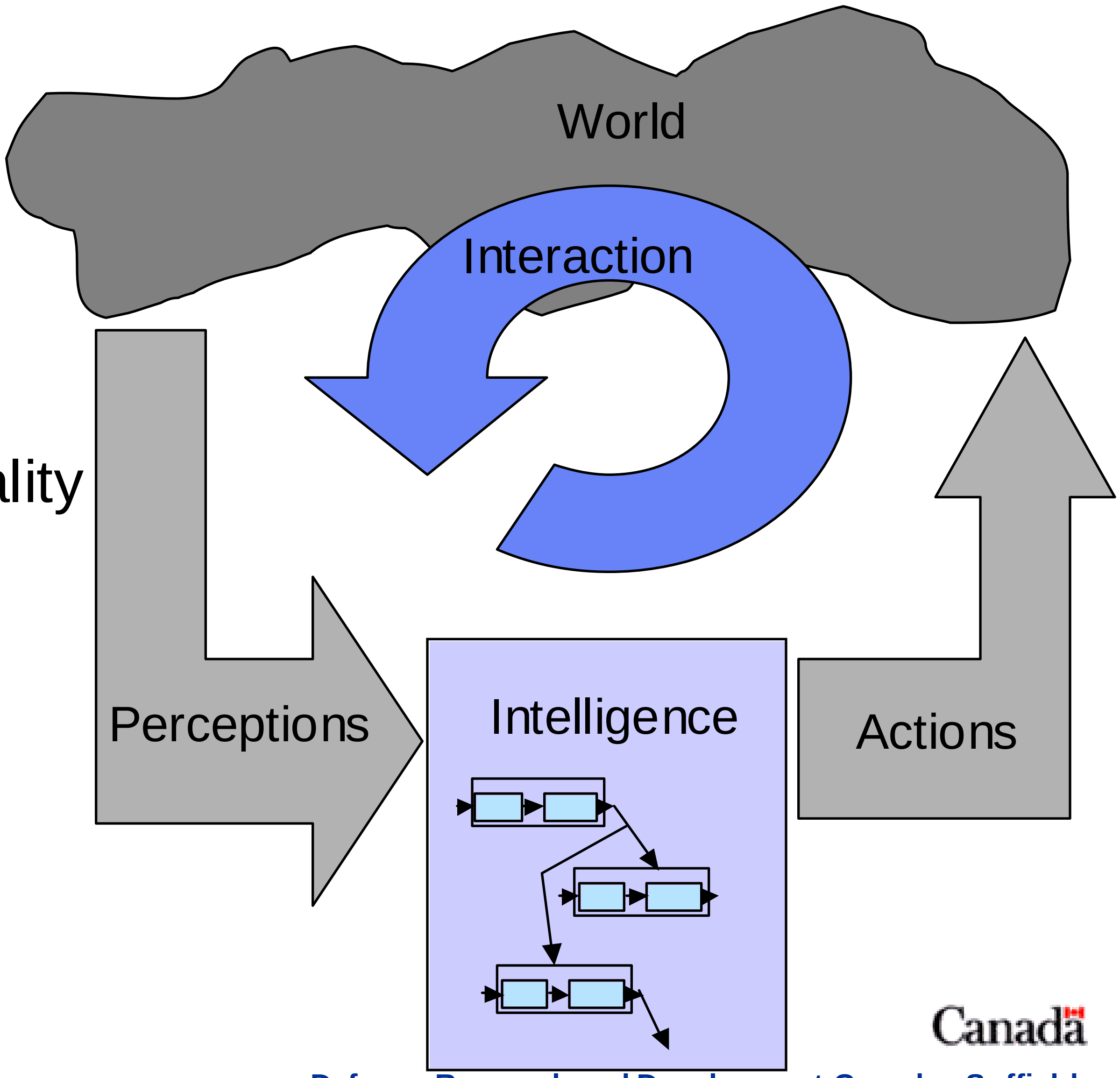
- The world is unstructured
- Required performance is high
- Autonomy research ignores many difficulties
- What are reasonable expectations

Outline

- Research streams
- Critical barriers
- Disruptive impact of autonomy
- DRDC - Autonomous Land Systems Program Demo

Autonomy Control

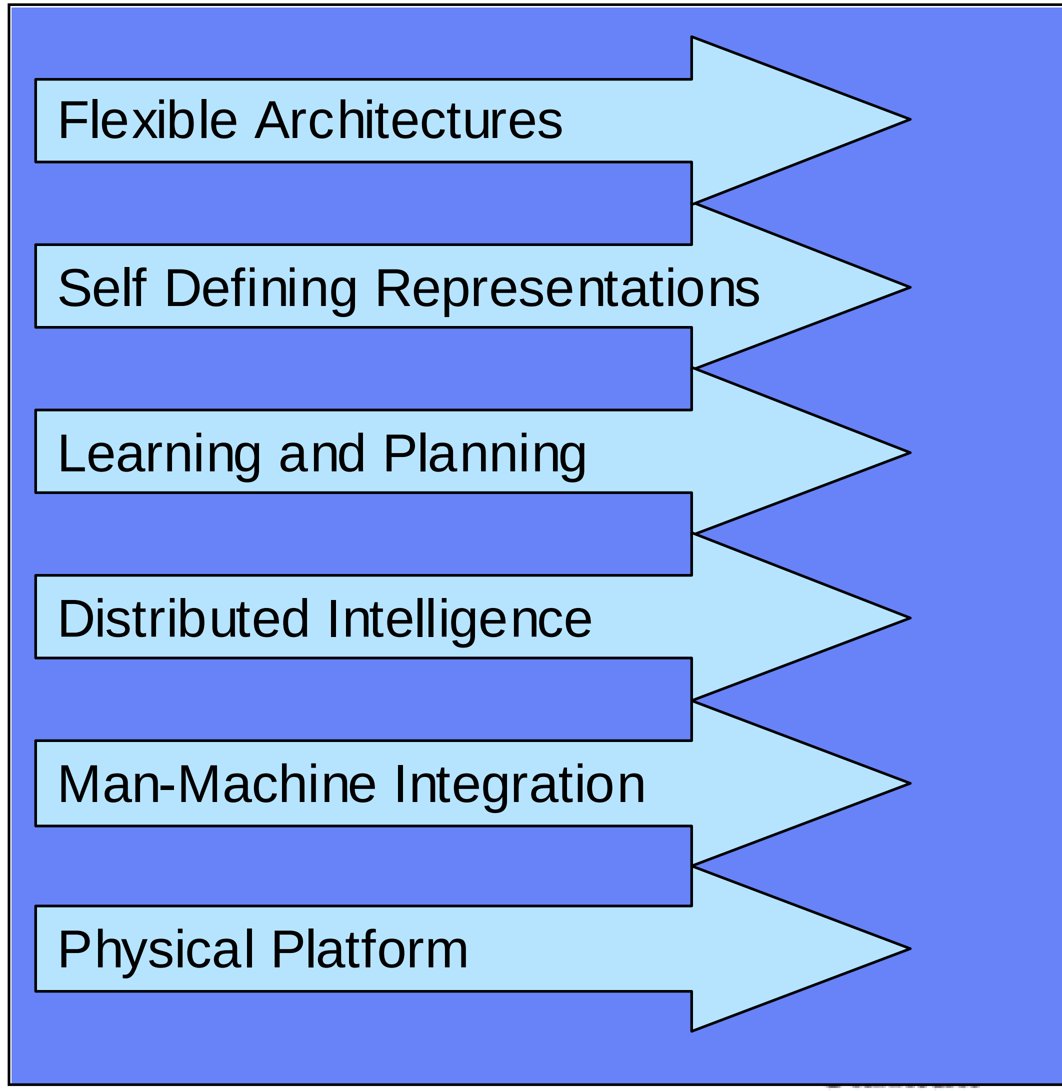
- Self controlled
- Self directed
- Self evaluating
- Self improving
- Broad functionality
- Self sustaining
  - fueling
  - reproducing



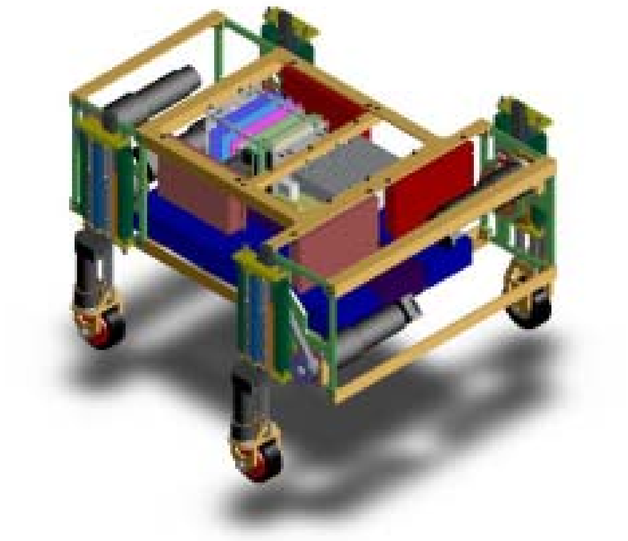
Research Streams

Interdependent streams require:

- Research coordination
- Unified development infrastructure



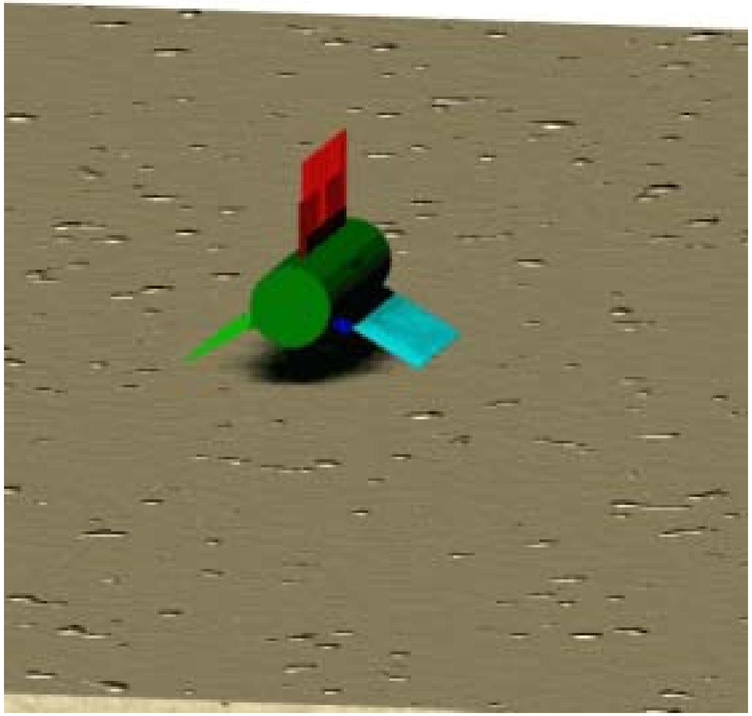
RS1 – Physical Platform



- Intelligence interacts with the world through the platform
- Ultimately determines vehicle use
- Needs to be broad purpose
- Unmanned vehicles not constrained by human limitations
- Resilient enough to survive failing (important to learning)

RS1 – Physical Platform 2003

Rhex - McGill

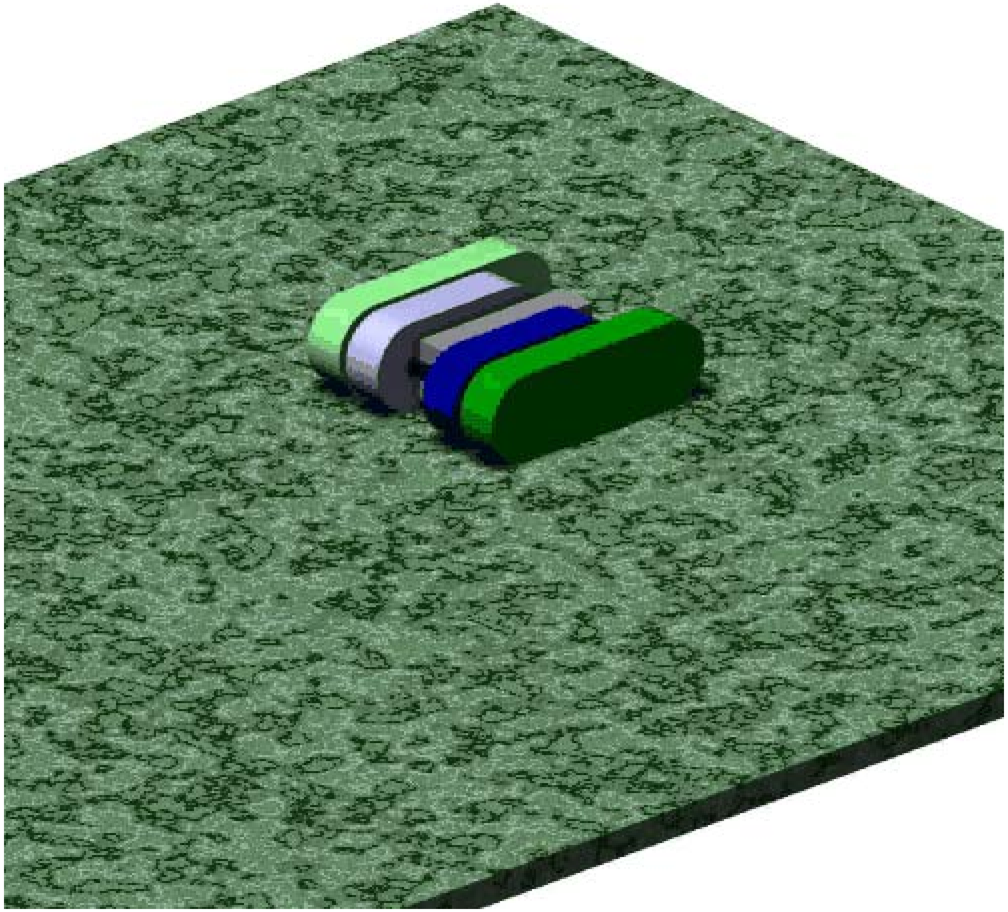


Conformal robots – urban/rubble

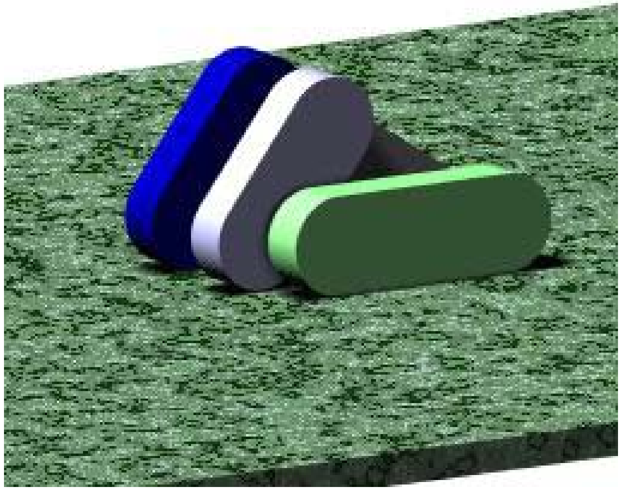
- Limited mobility (mostly wheels and tracks)
- Legs (static stability)
- Simulations of modular robotics
- Mechantronics –
  - unified integration of mechanical and electronic components.

RS1 – Physical Platform 2010

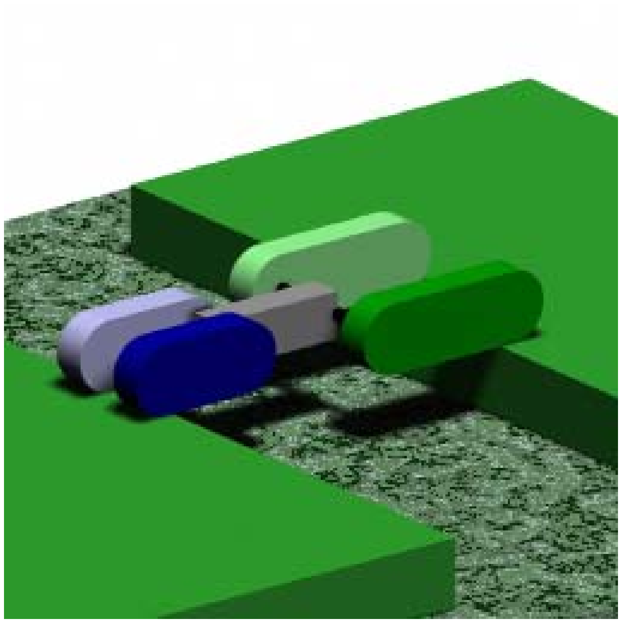
- High utility robots
  - shape shifting
  - multi mode
  - general purpose
- Tethered distributed robots
  - Full use of tether for mobility, navigation, comm and power



RS1 HUR-Badger

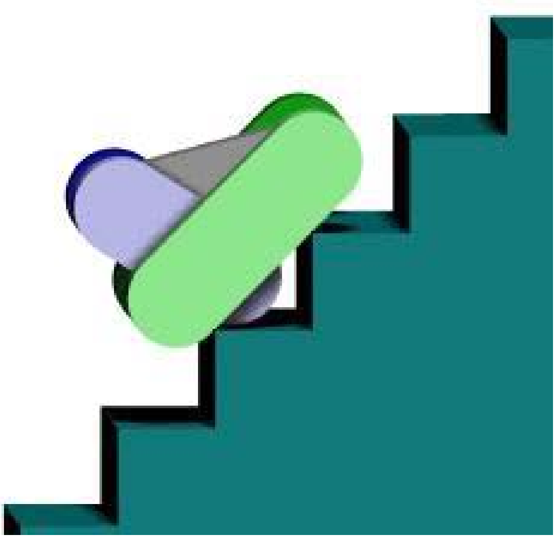


Forward Wedge: Counter rotating tracks for moving under wire and rubble

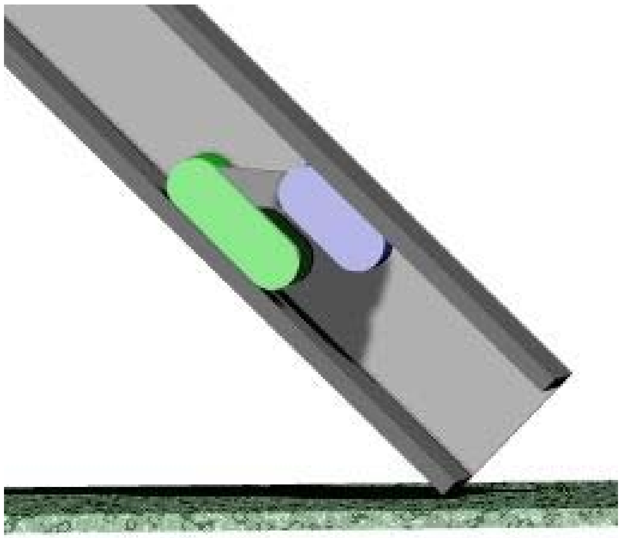


Full Extension: Bridging gaps and distributing weight

RS1 HUR-Badger

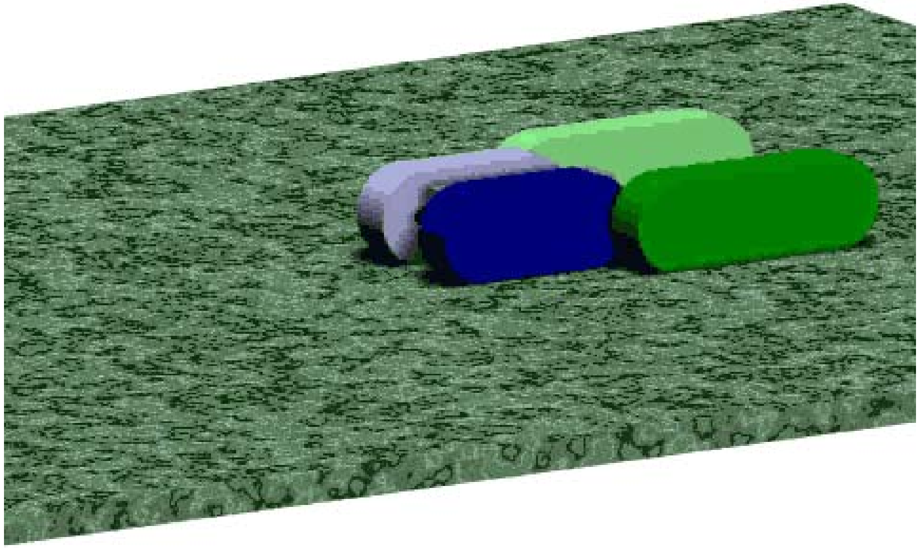


Stair Ratchet: Climbing stairs too steep for tracks



Duct Climb: Climbing vertical pipes and ducts

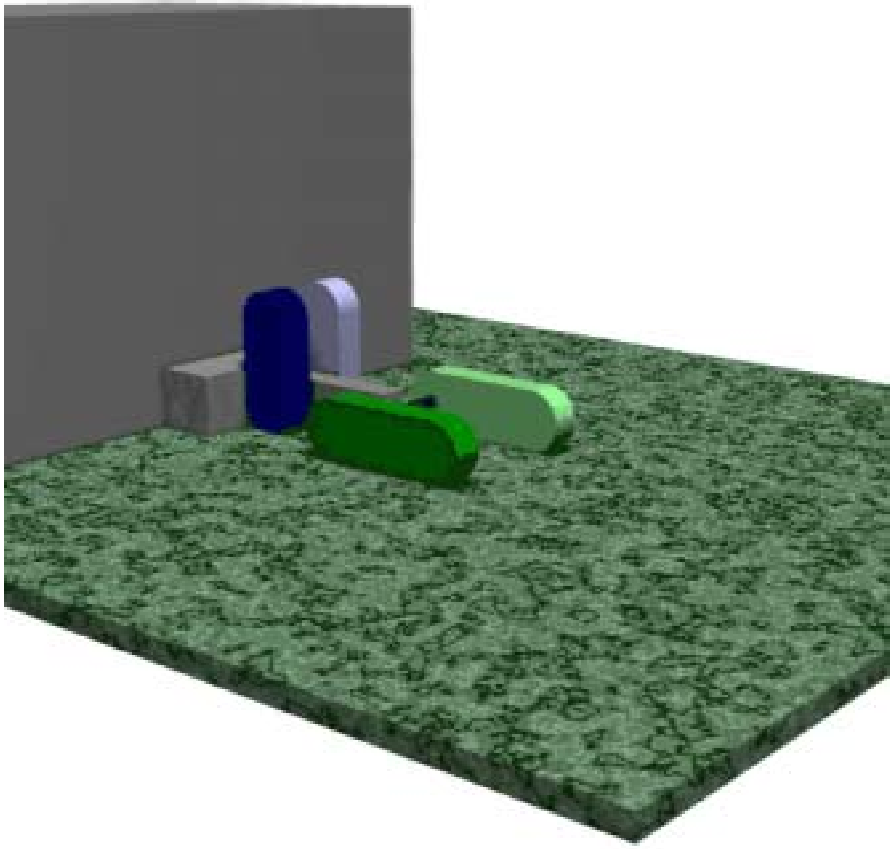
RS1 Snow Shoeing



Soft soil, snow and large granularity rubble

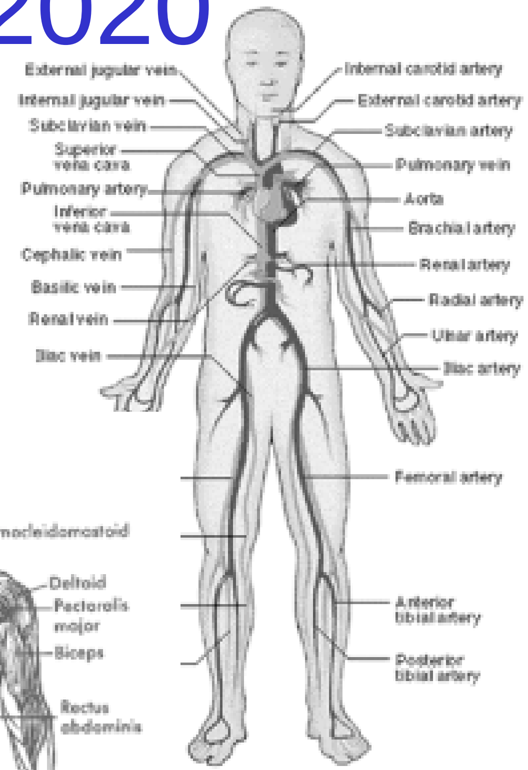
RS1 Loader

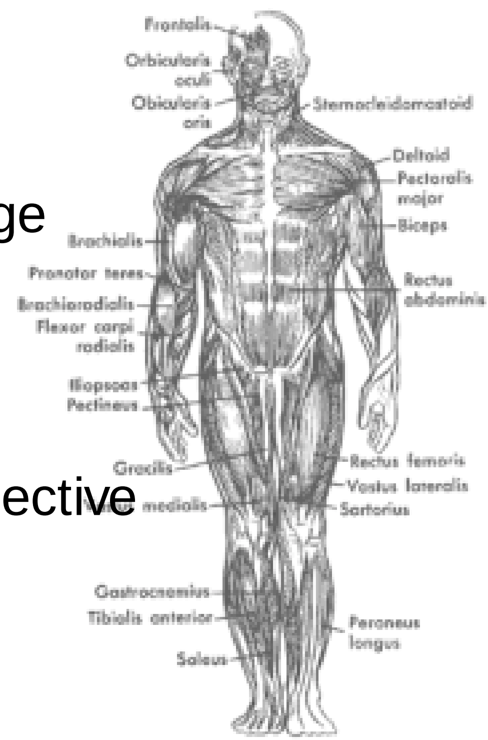
- Volumetric modeling of world
- 3-D path planning
- Multi -mode paths
- Shape transformations
- Intelligent engagement of the terrain



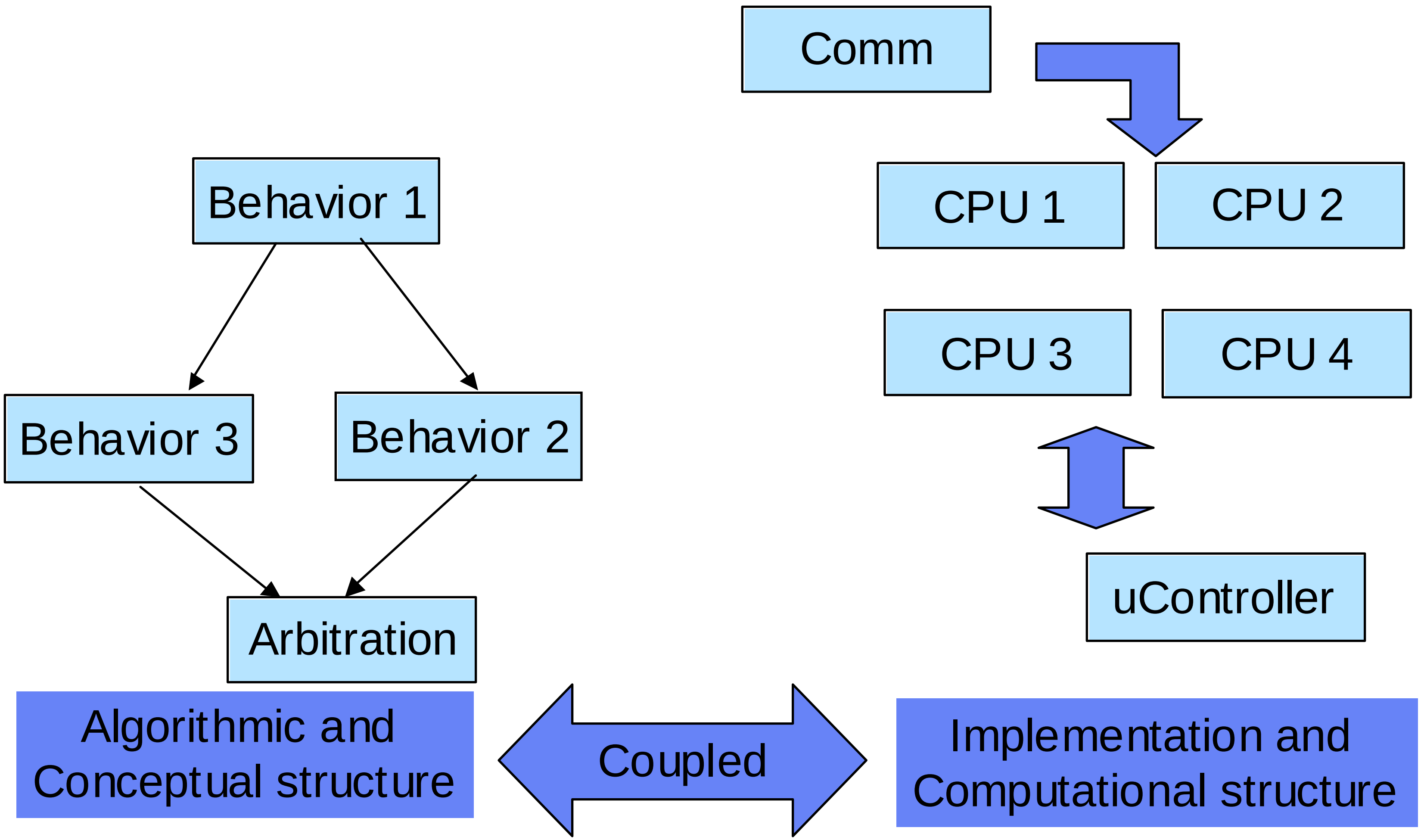
RS1 – Physical Platform 2020

- Adaptive physical shape and strength
- Self repairing
- Exploitation of dynamics
- Beyond mechatronics
  - Strength elements
  - Electronics
  - Power transmission and storage
  - Sensing
  - Communication
  - Actuation
- Ie skin is both a sensor and a protective barrier





RS2 Flexible Architecture



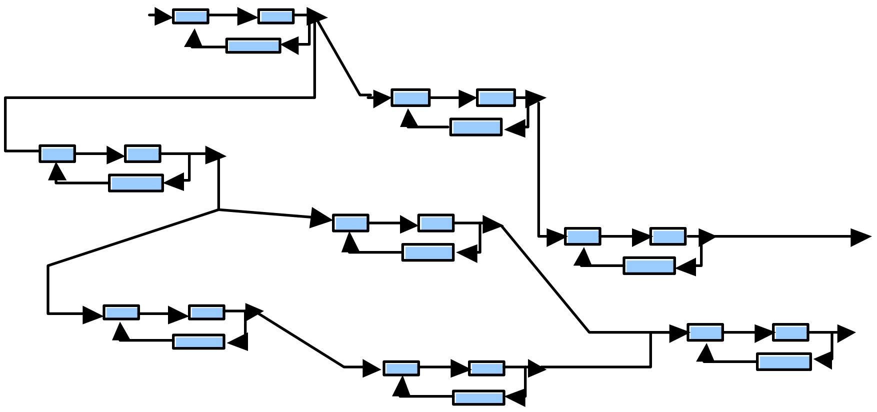
RS2 Flexible Architectures 2003

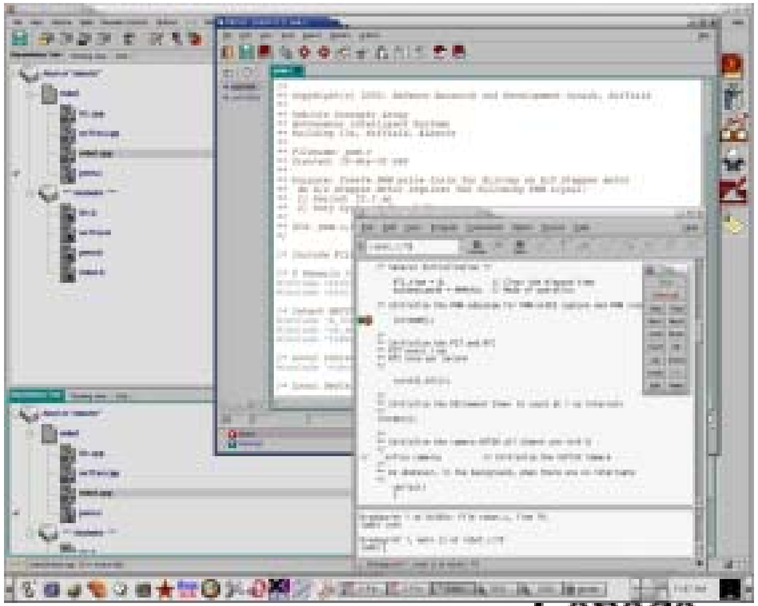
- **Implementation**
  - Software rule based
  - Analog circuitry
  - Implemented on monolithic or distributed computational resources
  - Realtime control

- **Algorithmic**
  - Preemptive behavior based
  - Hierarchical behavior based
    - Fixed
    - Learning
  - Time critical processes

RS2 Flexible Architectures 2010

- **Algorithmic flexibility**
  - Self generating control structure and interconnectivity
  - Incorporation of learning, planning and task decomposition



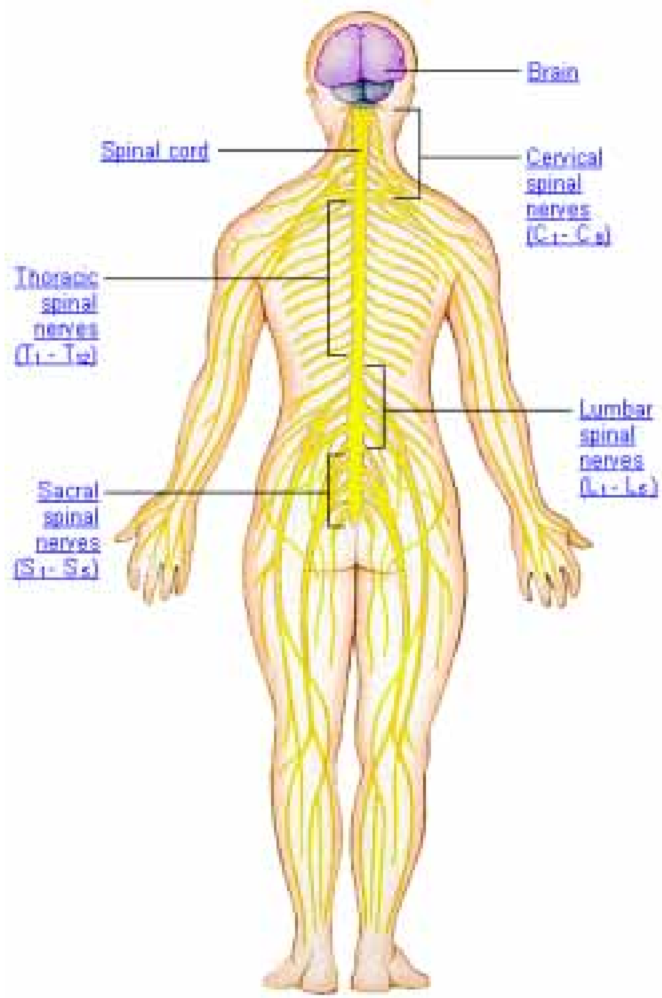


- **Hardware platform flexibility**
  - migration of algorithms between processors

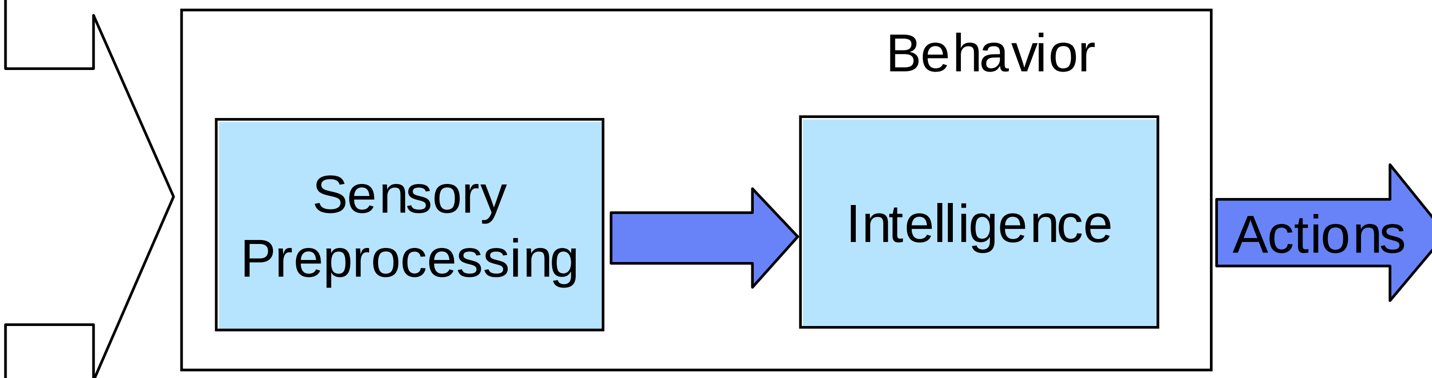
RS2 Flexible Architectures 2020

- **Biological intelligence architectures**
  - Implementation structure and algorithmic structure linked
  - Interwoven asynchronous control loops
  - Adaptable framework and resource allocation

- Duplicate in analog circuitry (adaptive hardware) or simulate in digital?



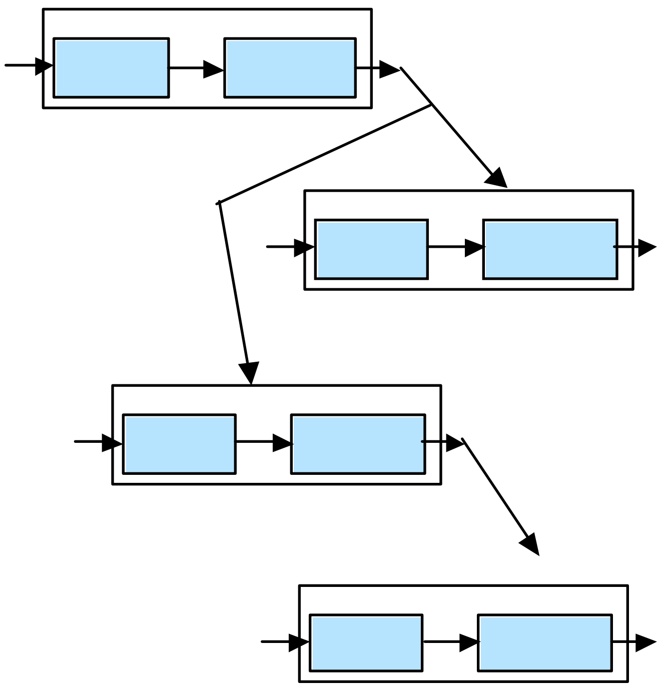
RS3 – Learning, Planning and Discovery



- Unstructured worlds and broad task range require
  - Learning,
  - Planning,
  - Discovery,
  - Generalization,

RS3 - Learning 2003

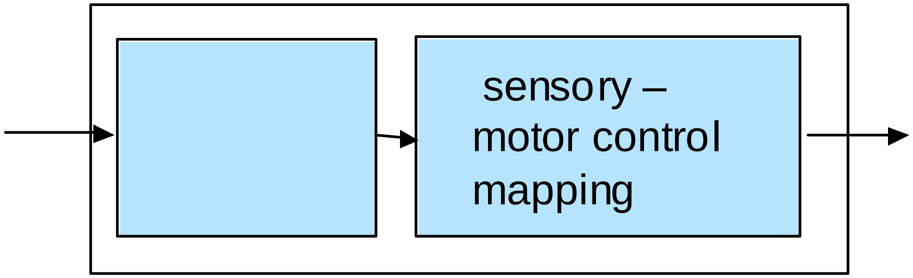
- **NN supervised learning**
  - NN training costs prohibitive
  - Locally weighted regression
- **Bayes methods**
  - web search
  - Kalman filtering, SLAM
- **Reinforcement Learning**
  - temporal credit assignment
  - the curse of dimensionality
- **Hierarchical structure**
- predefined and connections set by hand in advance
  - Requires prior knowledge
  - Limits autonomy

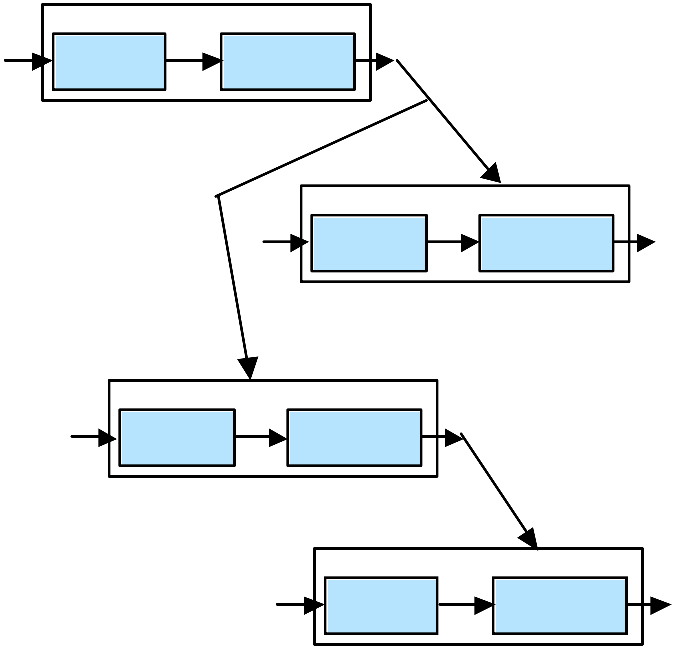


Pre-constructed Hierarchical Structure of Behaviors

RS3 - Learning 2010

- Learned structure and behaviors
- Decomposition into basic concepts
- Apply concepts to new problems
- Abstraction of actions and sensory
- Planning based on learned models
- One shot learning
- Discovery of new behaviors





Learned Monolithic Solution

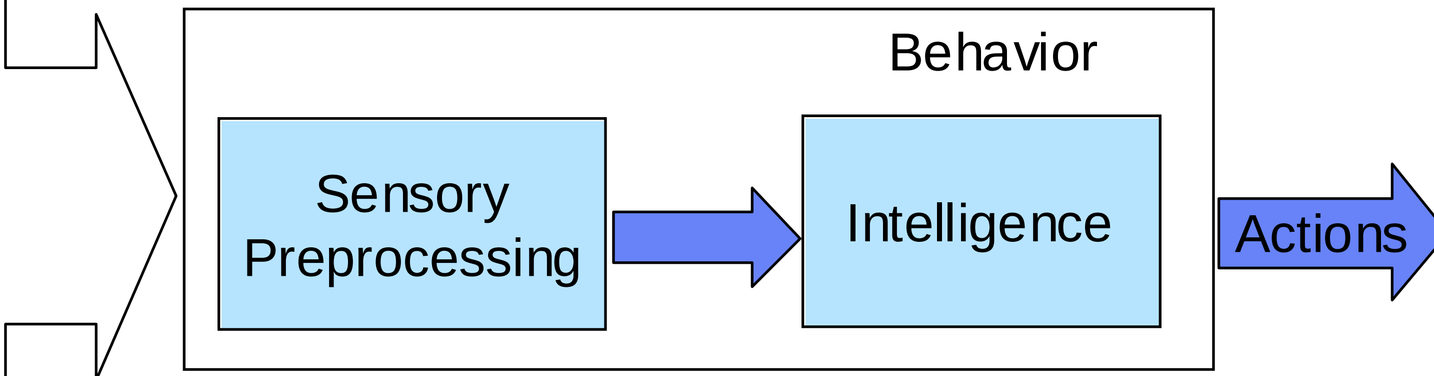
Learned Control Structure

RS3 - Learning 2020

- Learning occurs asynchronously across different tasks and timescales
- Self organizing learning combining own experiences, informal observations of others and information from others
- Planning based upon learned model of abstraction

- Zero shot learning -Good enough extrapolation
- Good enough – fast enough solutions

RS4 – Self Defining Representations



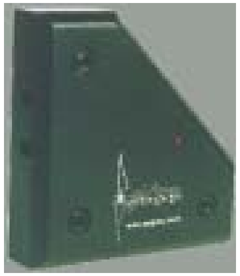
- Sensory preprocessing required to :
  - Reduce complexity of world
  - Define sub goals
  - Establish success criteria
  - Bound responses
  - An open problem – how can we automate

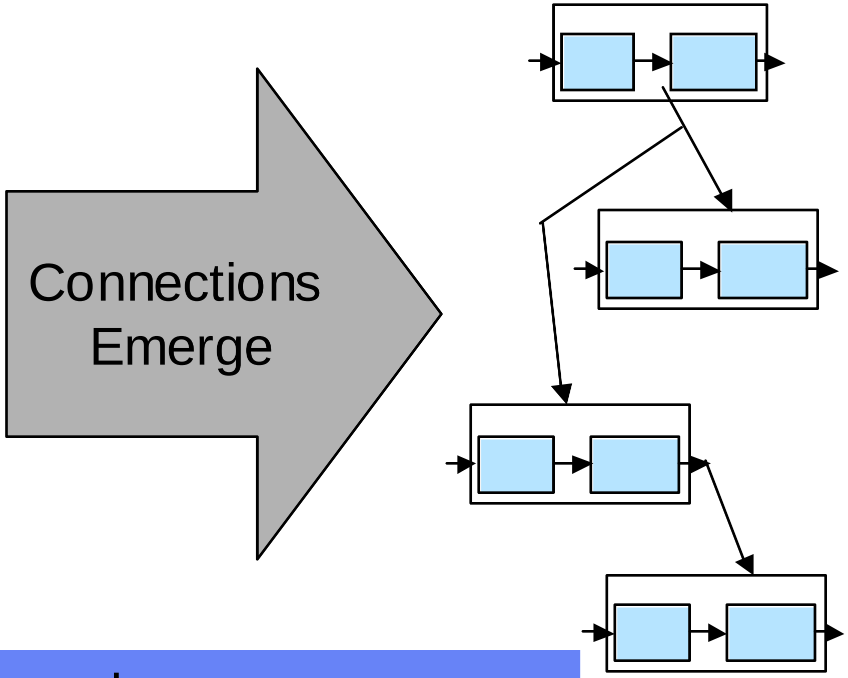
RS4 - Self Defining Representations 2003

- Predefinition is acceptable
  - predefine relevant sensors
  - pre-specify useful sensor patterns
  - pre determined reflex actions
  - pre define architecture
- Control and learning occurs in a much reduced setting
- Biological entities define connections, patterns and responses:
  - evolution
  - learning
- What level of pre-wiring and bootstrapping is acceptable in autonomous machines?

RS4 - Self Defining Representations 2010

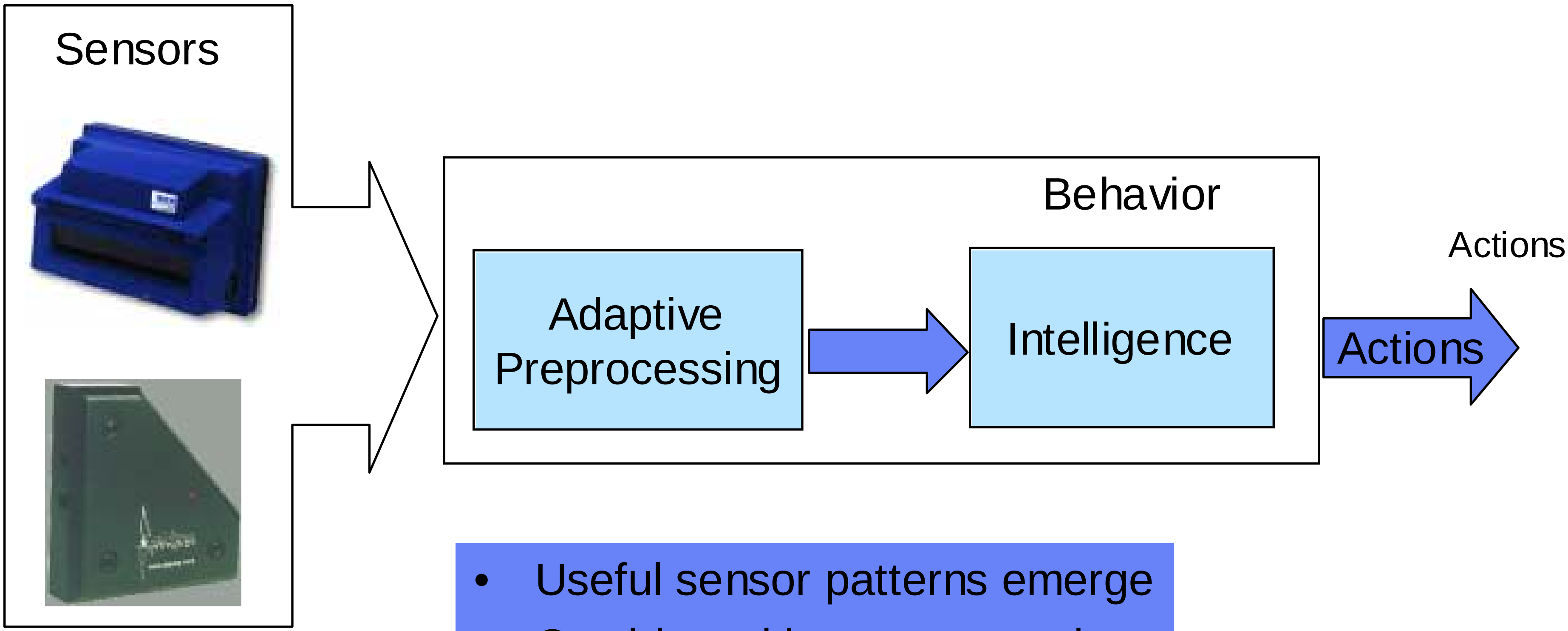
- Self generating connections
- New connections are constantly are added as they become relevant





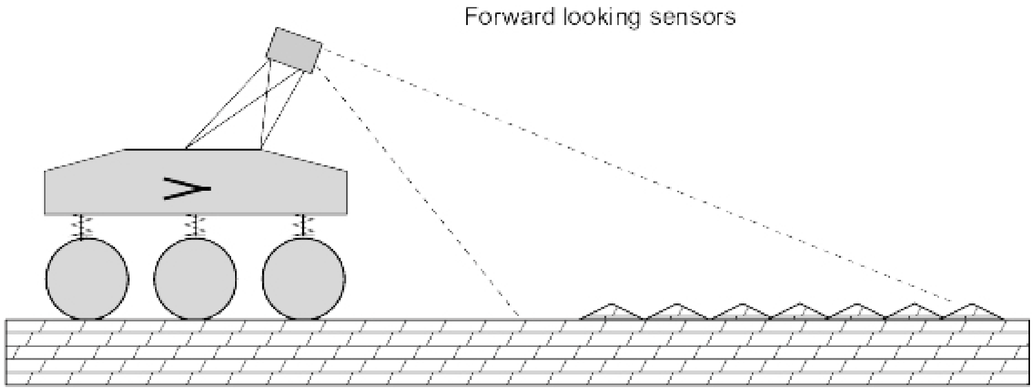
Learned connectivity, structure and patterns become representative of the environment and profession of the robot

RS4- Self Defining Representations 2020



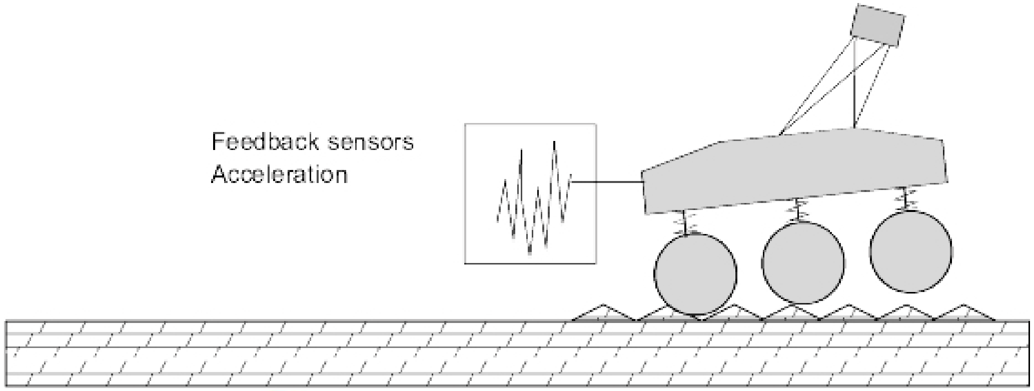
- Useful sensor patterns emerge
- Combine with structure and behavior learning sensory-motor abstraction emerge

RS4- Self Defining Representations Learned Trafficability Models



Perceives terrain characteristics

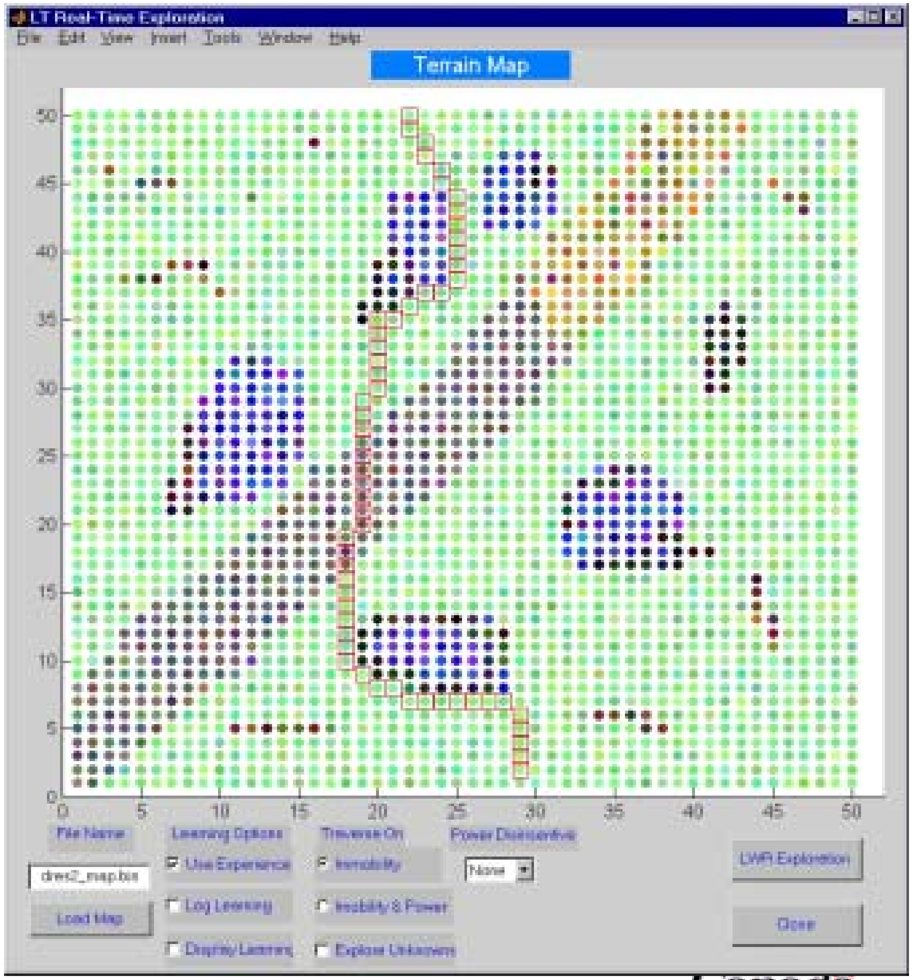
Experiences trafficability characteristics



Associate perceivable characteristics with trafficability characteristics

RS4- Self Defining Representations Learned Trafficability Models

Planning based upon learned models



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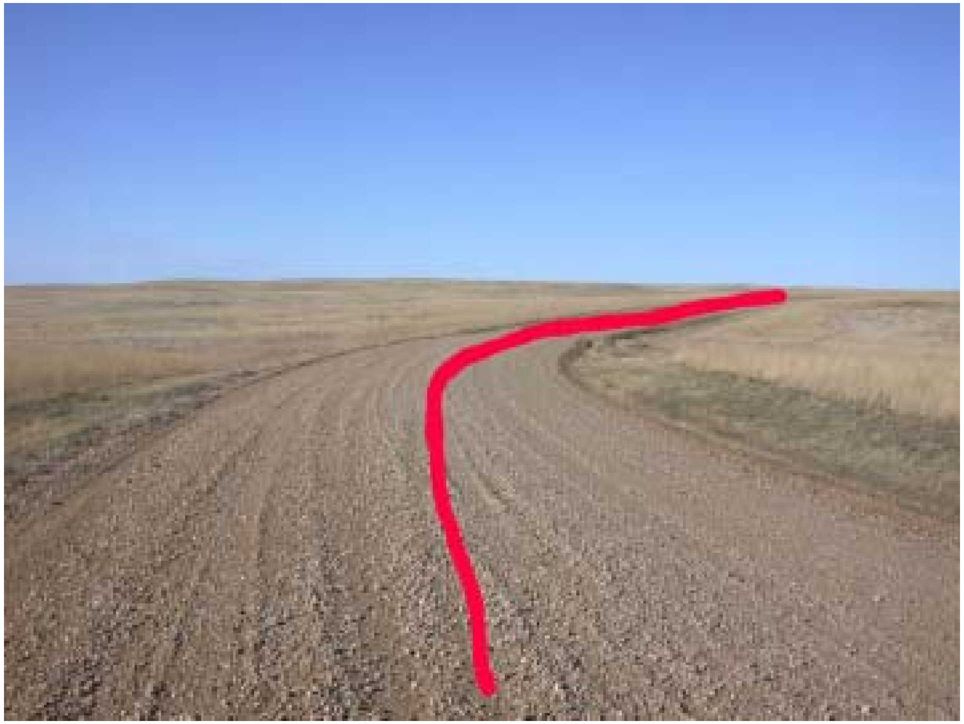
RS4- Self Defining Representations Learned Trafficability Models

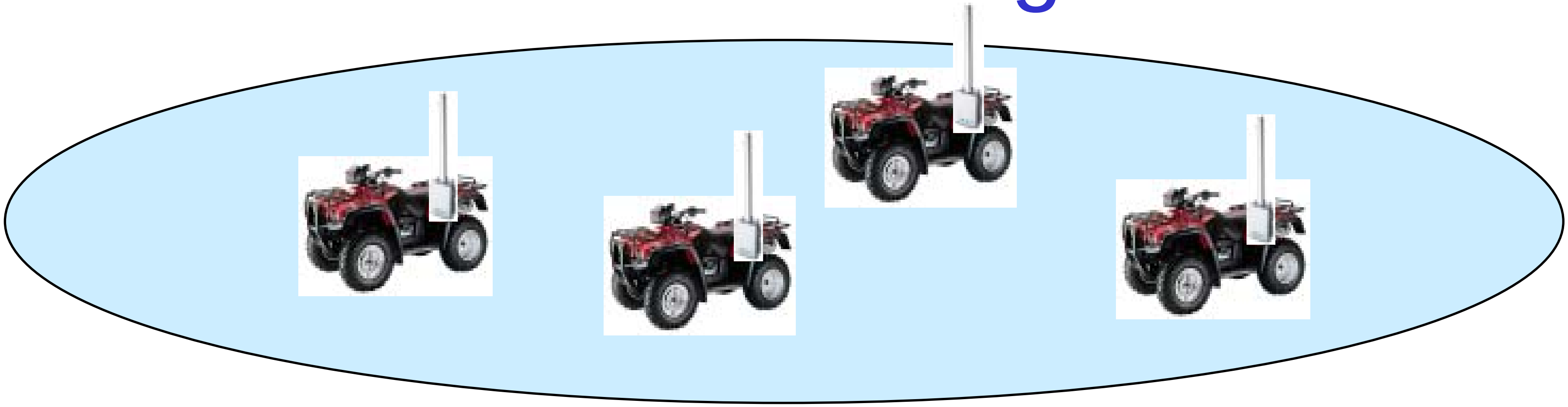
Learned Terrain Effects Models in 2-D

RS4- Self Defining Representations Learned Trafficability Models



Path inferred by terrain models in 2-D view – Beyond range of 3-D sensors

RS5- Distributed Intelligence



Two paradigms for distributed control

1. Simple rule based local interactions -Insects
2. More complicated interactions – humans

- Simple niche entities vs general purpose entities
- No central point of failure
- Command and control of 10s 1001 and 1000s of autonomous entities.

RS5-Distributed Intelligence 2003

Complex interactions

•Market based – auctions with pre-defined commodities

•Dynamic role allocation

•Share information – maps,

•Cooperatively localize

•Communal learning

•Pre-programmed interactions

•Centralized control

Simple local interactions based upon:

- Immune system
- Physics
- Pheromones
- Ant
- Birds

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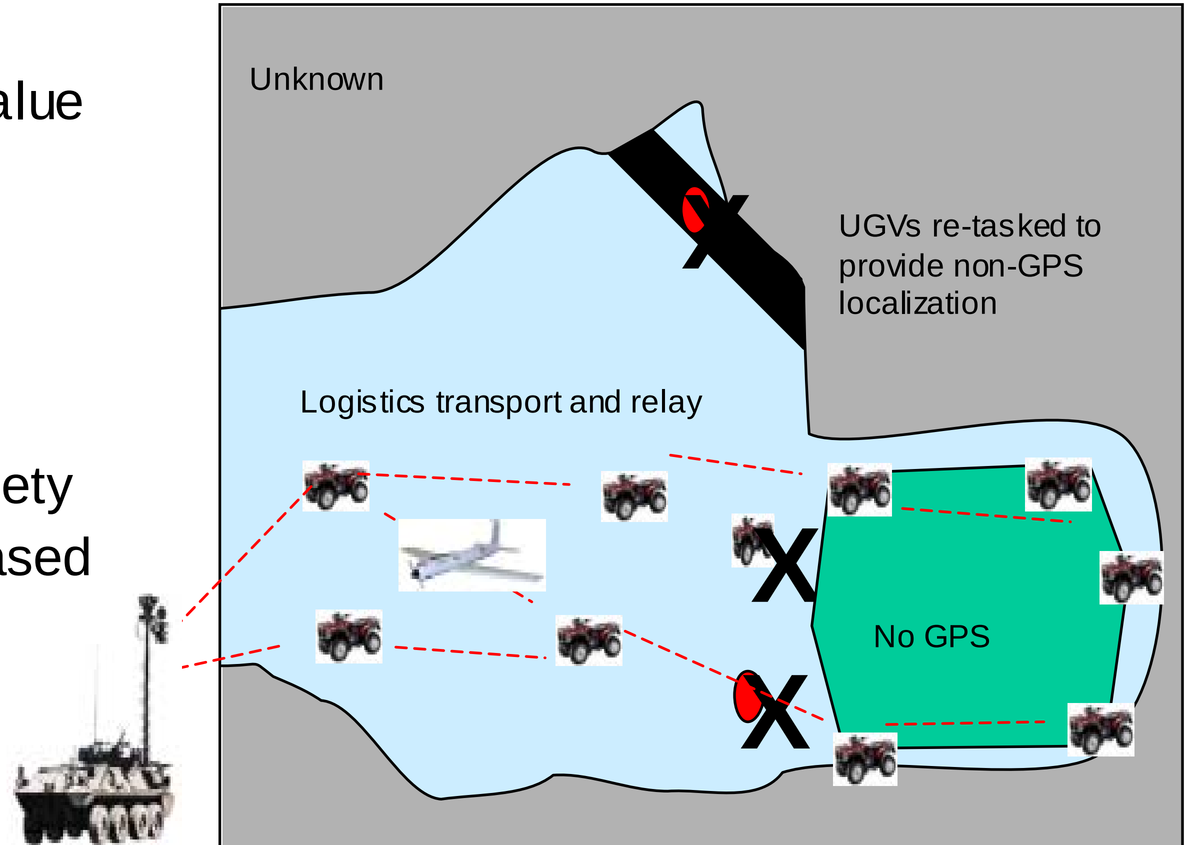
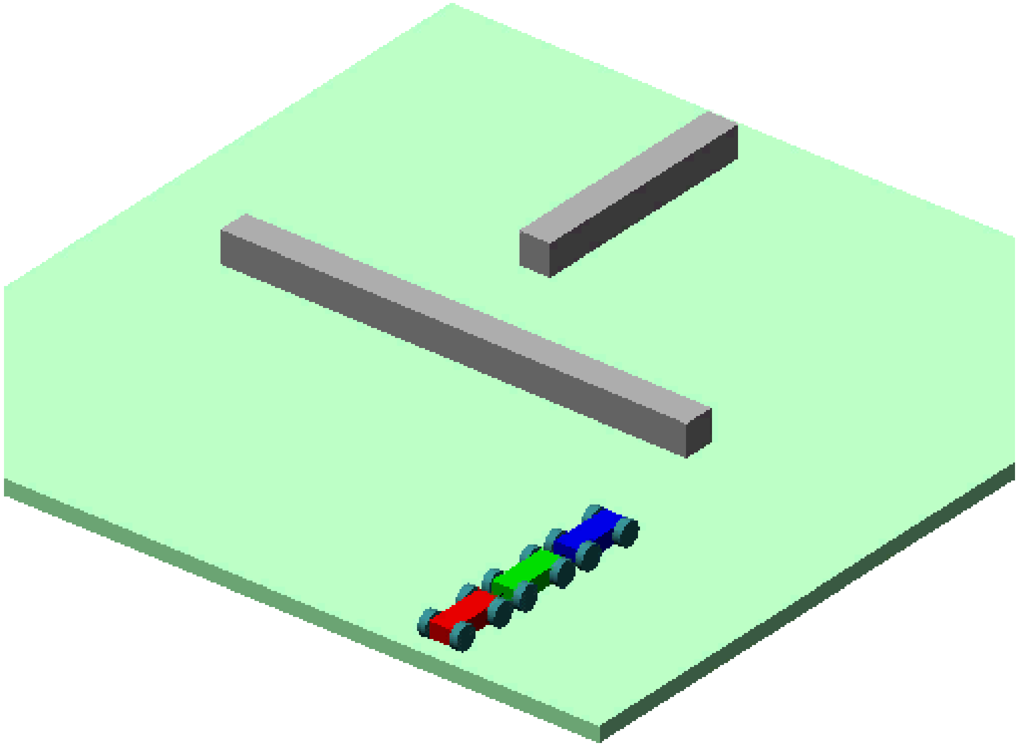
RS5 – Distributed Intelligence 2010

- Diverse commodity market based control
- Learned commodity value models
- Efficient specialization
- Centralized planning
- Communal learning – intelligence and adaptability of the society
- Re-taskable swarm based coordination



RS5 – Distributed Intelligence 2020

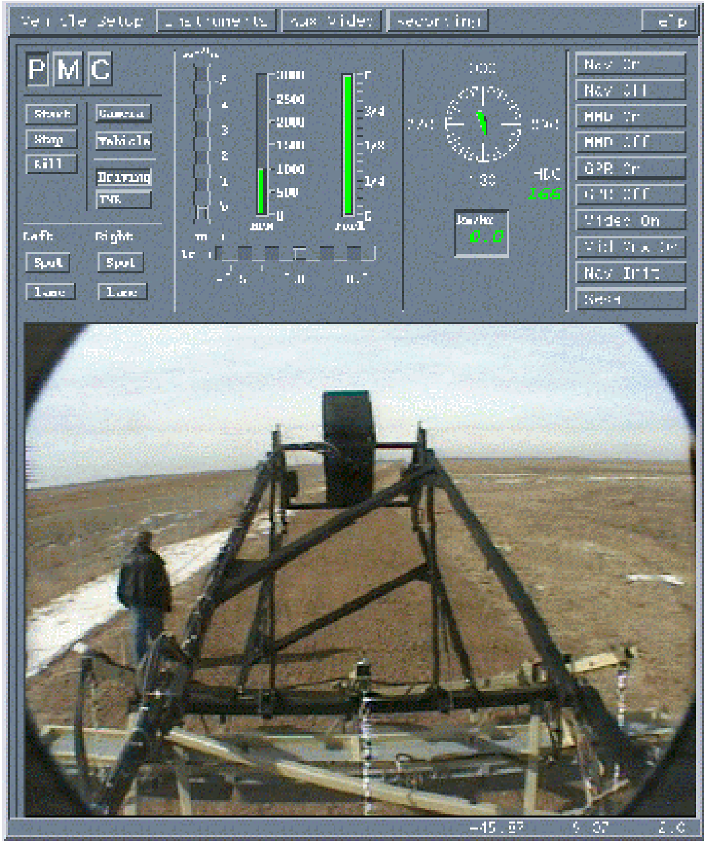
- Commodity discovery
- Predictive modeling of teammates
- Fluid and graceful team behavior
- Parallel capability exploitation in role allocation



Theseus –Tethered Distributed Robotics

RS6- Man-Machine Integration

- How do humans
  - Control machines (even 1000s)
  - Understand what machines are doing
  - Assist machines
  - Teach machines
- Interfaces
  - tele-operation (many to one vehicle)
  - intervention
- Human factors for interface design
- Apprentice systems
  - Simple memorization
  - Learning through imitation



ILDP Teleoperation Interface

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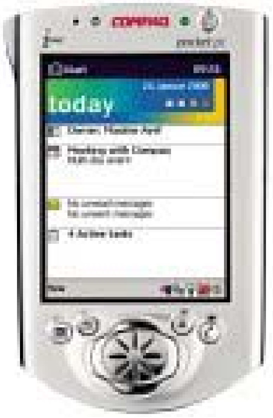
Defence Research and Development Canada - Suffield

RS6 – Man – Machine Integration 2003



- Interfaces though which humans interact with machines
  - Sliding autonomy
  - Shared control
- Operators assists (auto pilots)
- Human factors – console
- Many operators teleoperating a single vehicle
- Apprentice systems: humans teaching learning machines

RS6- Man-Machine Integration 2010- Apprentice Systems

- Learning machines will need to be prepared for future endeavors much the same as humans or at least animals
- Training methods
  - Graduated complexity
  - Scripted lessons
  - Imitate a human or experienced machine
  - Scaffolding
- Once trained to an acceptable level of performance, machine will continue to learn and improve autonomously.
- When faced with significantly different contingences the machine can learn how succeed autonomously.

RS6- Man-Machine Integration 2020

- Interfaces for one operator controlling 1000s of vehicles
- Humans and robots working in close proximity
- Robots learn predicative models of other robots humans
- Team behaviors built on predictive models
- Model and exploit adversary's weaknesses
- Through practice teamwork is refined to a point where graceful, reactive responses to dynamic situations

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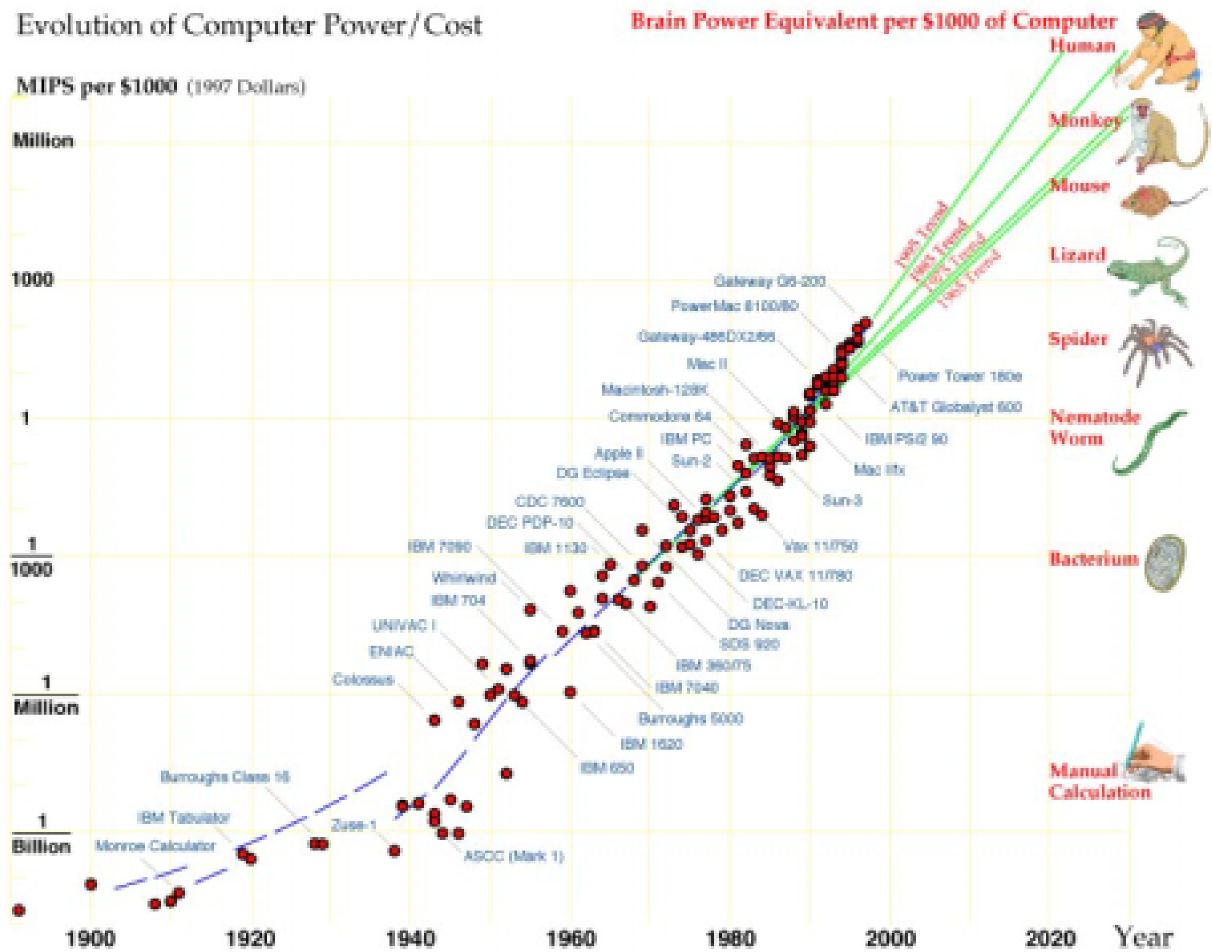
Critical Barriers

CB1 – Computational Power

Moore's Law



Courtesy of Hans Moravec

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Defence Research and Development Canada - Suffield

CB2 – Algorithmic Intelligence

- Moore's law dictates ever increasing computation power and has held across many paradigms
- Necessary but not sufficient for machine intelligence
- Algorithms that embody intelligence are the real requirement
- Need
  - Algorithms that scale up
  - Algorithms that are implementable
  - Unified approach

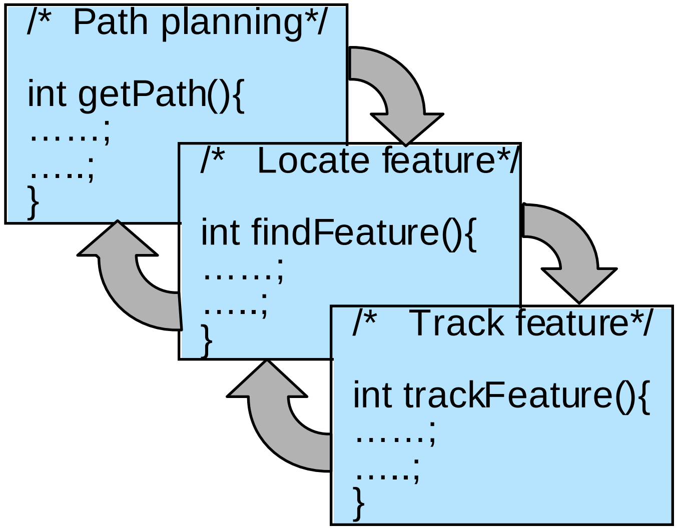
CB3 Sensors

- Interpreting sensors especially vision very difficult
- Most autonomy researchers rig vision system – let vision researchers do it
- Vision systems require prior knowledge and set up
- Fail in many ways
  - To bright
  - Shadows
- Large part of brain used for vision

DRDC-V Benoit Ricard

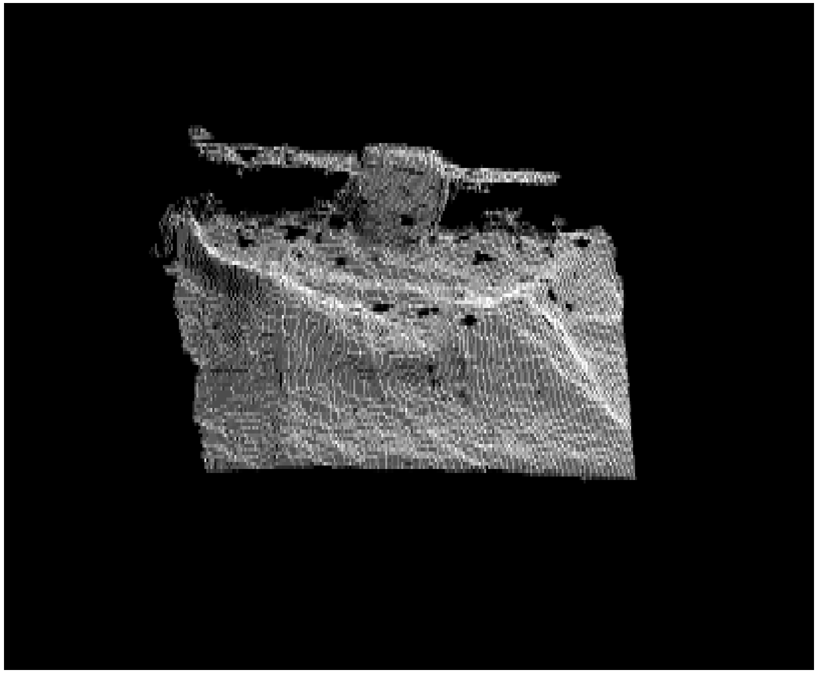
CB4 Mechanisms for Creation of Intelligence

- Biological intelligence is not serially executed instructions
- Heterogeneous adaptive structure
- Structure and responses set by:
  - by evolution
  - by experiences
- Will simulations of thought and physiological processes work



CB5 Representations for Creation of Intelligence

- Are the current languages adequate to create intelligence?
- Are the current representations adequate to create intelligence?
  - Analog signals
  - Symbolic
  - Neural Networks
  - Local parametric models
  - Bayes methods
  - Particle filters



CB6 – Autonomy and Trust

- Large and fast vehicles
- Soft humans
- Use of lethal force
- Zero tolerance of errors

- Trust mandatory for success
- Trust gained consistently reasonable actions
  - Difficult for robots working in unstructured environments
  - Even more difficult for learning robots
- How to constrain robots to act reasonably but still have the freedom to solve problems in creative ways?

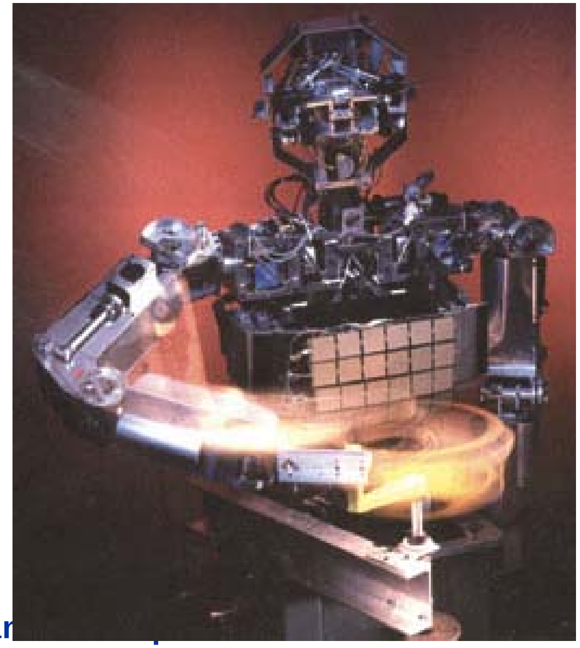
CB7 Adaptation Range

Courtesy of Hasbro

Niche creature :

- Short infancy
- Little learning through life
- Not useful outside of niche task
- Simple rules very robust
- Adaptation through attrition

Courtesy of MIT



Broad use creature :

- Long infancy
- Learns throughout lifetime
- Useful as an individual
- Can perform general tasks
- Subject to individual death

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Disruptive Issues

Capabilities that higher autonomy will enable that may pose a threat or an opportunity

D1 – Lethal Force

- Autonomous control of lethal force
- Different rules of engagement for machines

- Impossible to have a deterministic model of machine’s actions in a non-deterministic world
- With learning the machine’s operation changes based on experiences

- Who is accountability for mistakes
- Mistakes are tolerated in humans
- Will society be equally forgiving for machines

D2- Vehicle Operation Outside of Human Physiological Constraints

- Vehicles no longer need to house a human
  - Smaller, invertible, crashable,
- Unmanned vehicle does not need food or air
- Less effected by radiation, chemical and biological weapons
- Machines do not get fatigued or distracted
- Machines can distribute attention (pay attention to many things at once)

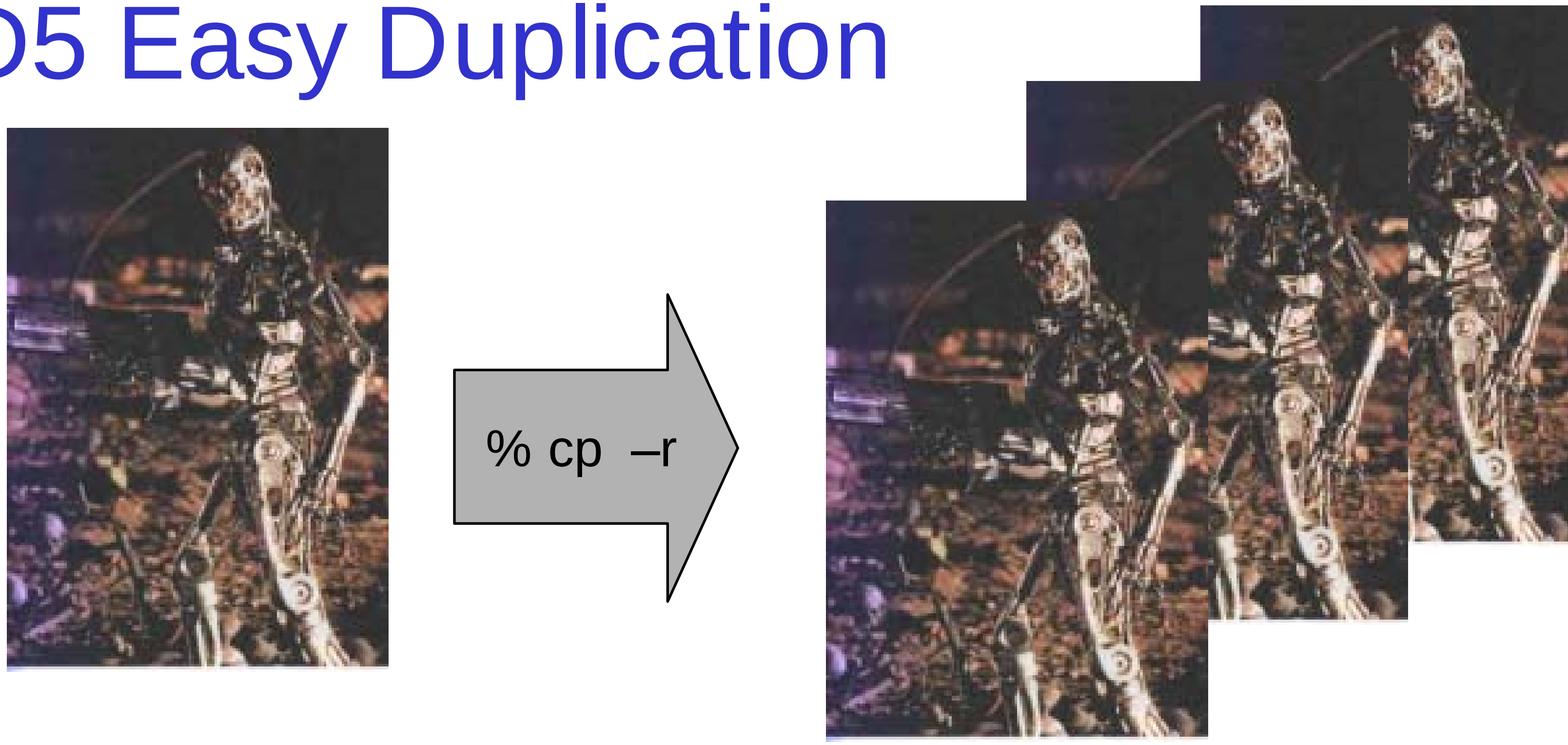
D3 Economics

- Automated vehicles may have the lifespan of many operators
  - No salary
  - No pension required
  - No health care
  - No legal costs (at least not on behalf of the machines)

D4 New tactics

- Huge numbers of expendable vehicles infiltrating enemy
  - New type of asynchronous threat
  - Pervasive information gathering
- Sacrificial vehicles
  - Prove routes ahead of human or expensive resources
  - Can be left behind
  - Kamikaze attacks

D5 Easy Duplication



- Human training a major investment in time and effort.
- Once apprentice systems are trained they can be easily duplicated
- Continued learning will supply human like variations to the individual robots

D6 – Persistent Knowledge

- Easy duplication of learned knowledge between machines fosters faster growth of communal knowledge
- Humans require years of training to acquire the state of the art, then become experts and then die.
- Machines can be educated as fast as knowledge can be copied.
- Machines could advance communal knowledge faster

D7 – Unquestioning Loyalties

- While commanders orders are to be followed, individual's moral sense will override the order if:
  - ordered to atrocities
  - ordered to treasonous acts
- Autonomous robots with no moral sense would not hesitate to perform immoral tasks
- Learning machines are a product of their experiences and training
  - Need to be influenced by ethics, morals

D8 – Loss of Moderating Influence

- Possibility of sustaining casualties a moderating effect to engaging in hostilities
- Potential of a casualty free conflict (at least on the side with autonomous systems) may make hostilities a more attractive option
- Technologically advanced countries would build
- Less advanced countries would purchase
- Weapons of mass destruction

D9 – Enemy Response

- How would an enemy fight against machines?
- Psychological effects on enemy:
  - Autonomous entitles cannot be scared, intimidated or become disenfranchised
  - Autonomous entitles would not show mercy
  - Humiliation in being beaten by the grandchild of your blender

D10 – Military Capability decoupled from population size

- Autonomous robots can be produced and fielded faster than biological entities
- Decouples country population from military capacity
  1. Stick **Least effective individual**
  2. Mechanization
  3. Informationization
  4. Automation **Most effective individual**

- Need to automate support as well as combat operations

D11-Decouple hatred from hostilities

- Sustained hostilities is a cycle of revenge based attacks and killings
- The loss of automated machines would not inspire a need for retribution
- Though the destruction of automated units would likely not satisfy the need for retribution

D12 Tight Coordination

- Communication between small team of robots.
- Each robot of the team would be perfectly aware of its teammates
- Perfectly coordinated swat team

D13 – Autonomous Swarms

- Many small vehicles (100, 1000, 10000s)
- Distributed local control
- Global effects
- No single point of failure
- Difficult to model and predict
- Difficult to control
- Small enough to infiltrate covertly
- Distributed low value target

The weakness of centralized control – Star Wars

Autonomous Land Systems Demo

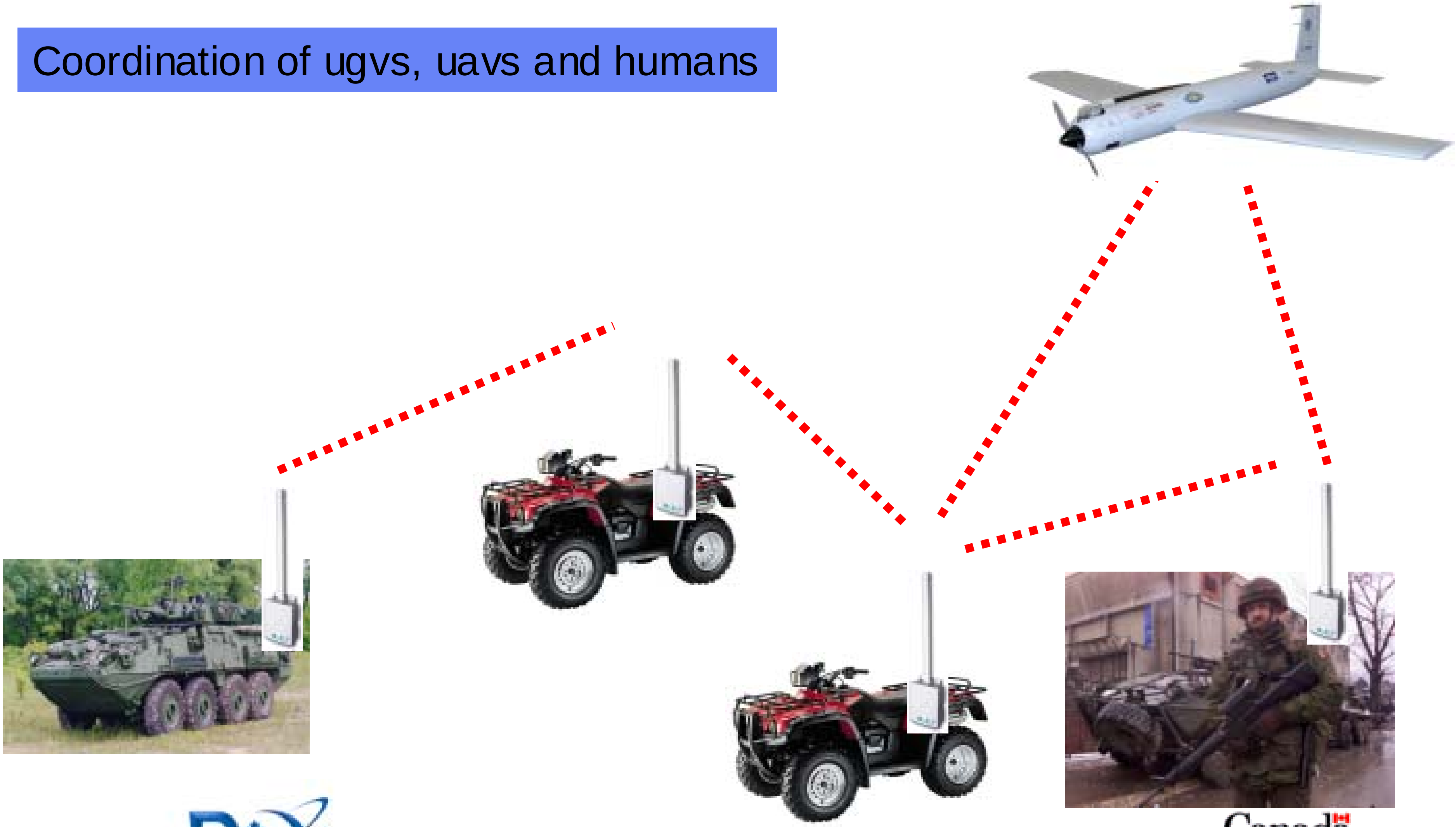
To increase independence of unmanned vehicles to a level at which they can perform given only high-level intentions in arbitrarily complex and dynamic environments

Program 2fm Demo (2005)

To demonstrate a team of autonomous ground vehicles performing a reconnaissance operation in the medium complexity environment of DRDC-Suffield.

Distributed Control

Coordination of ugvs, uavs and humans



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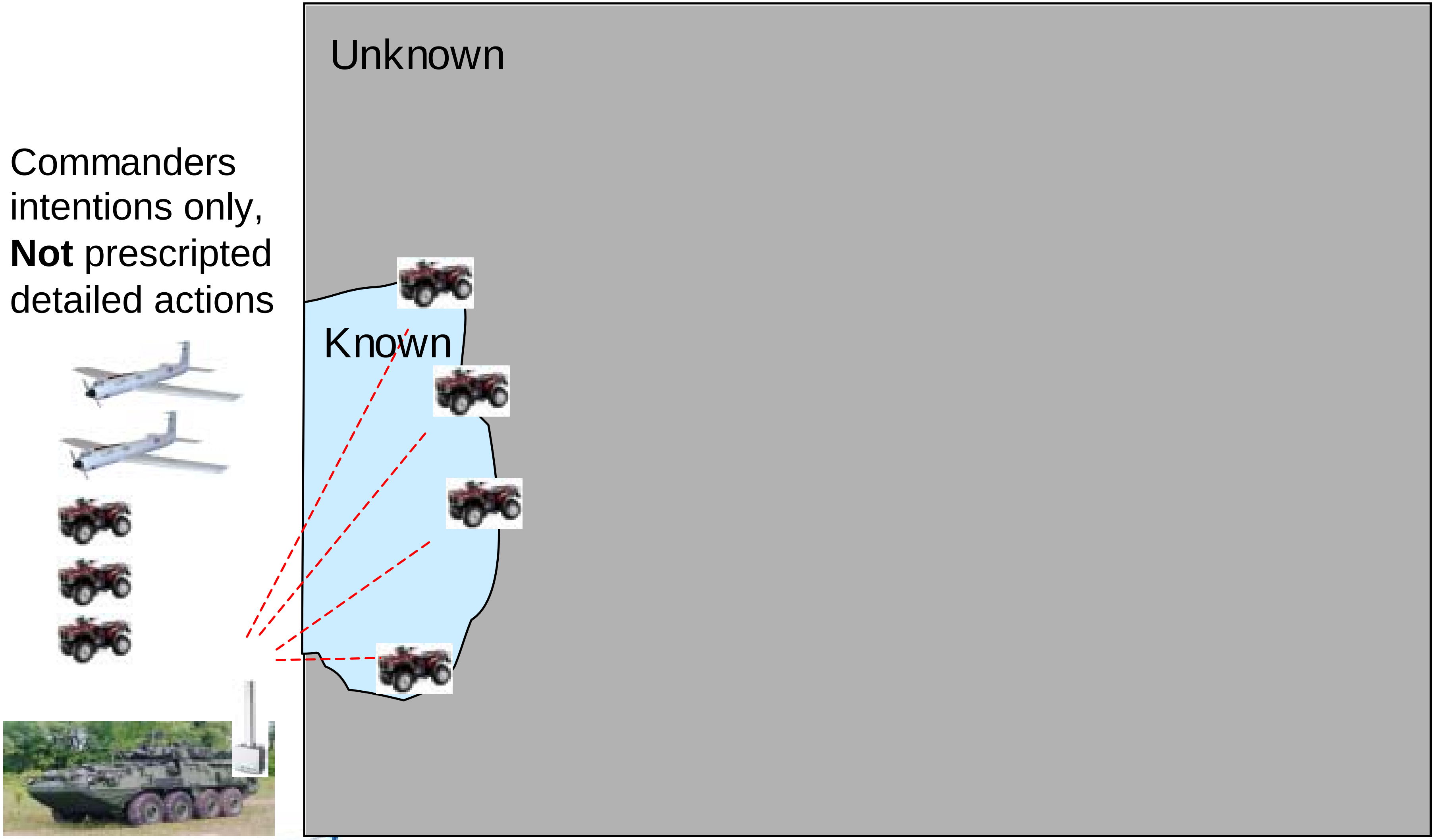
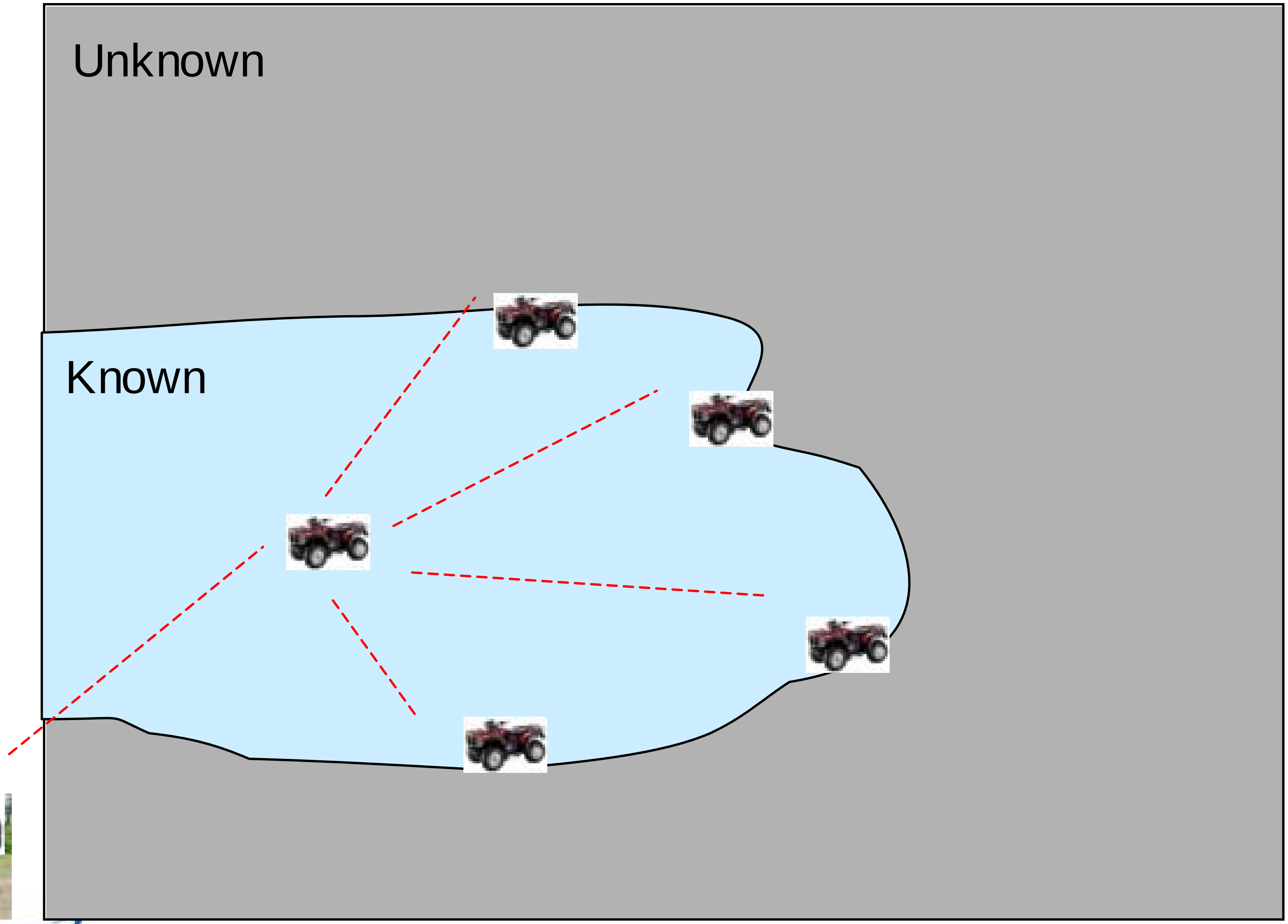
Mission Scenario Slide 1

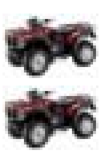
Commanders intentions only, **Not** prescripted detailed actions



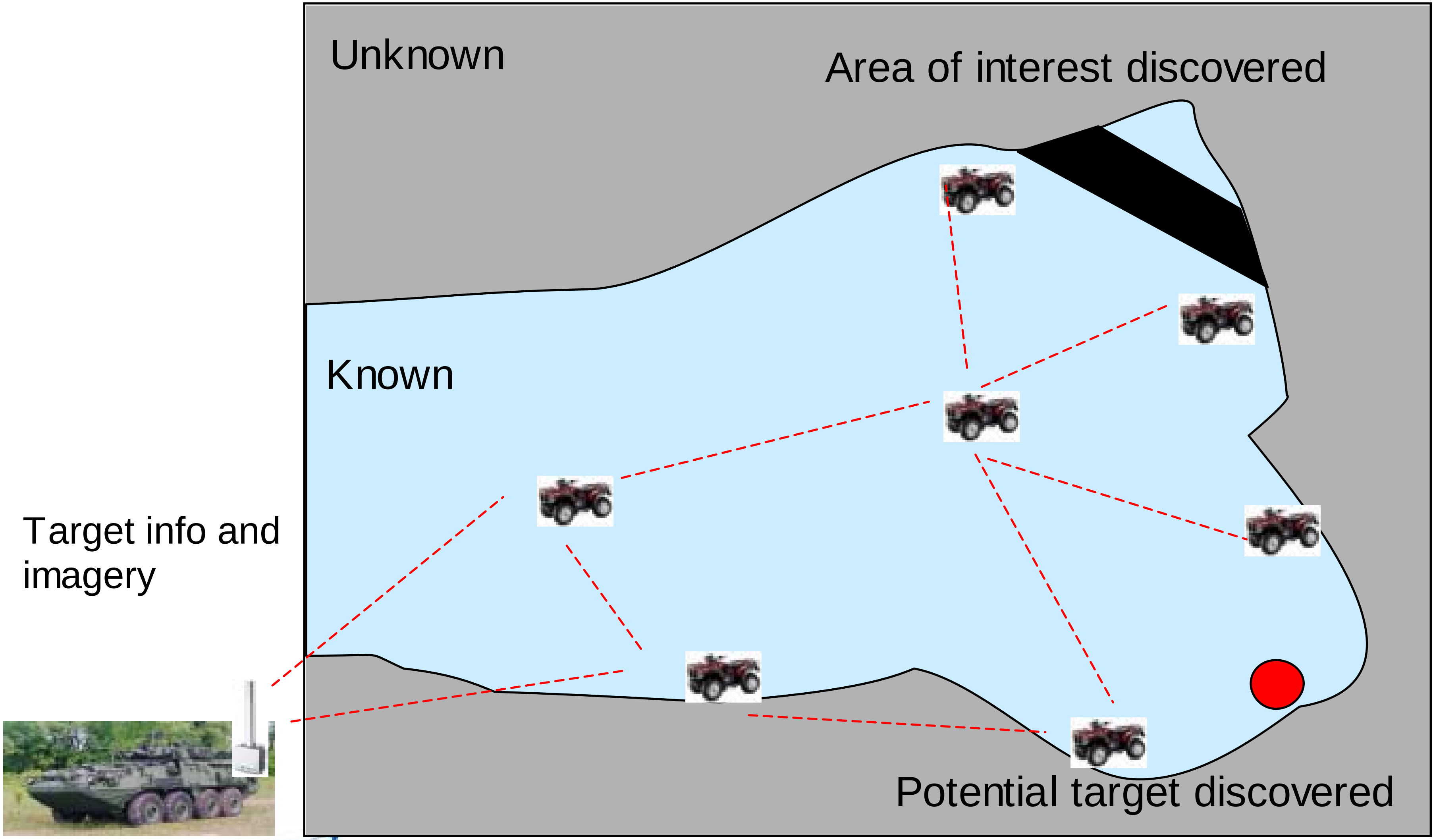
Mission Scenario Slide 2



Team Progress Reported (not realtime) and intention changes

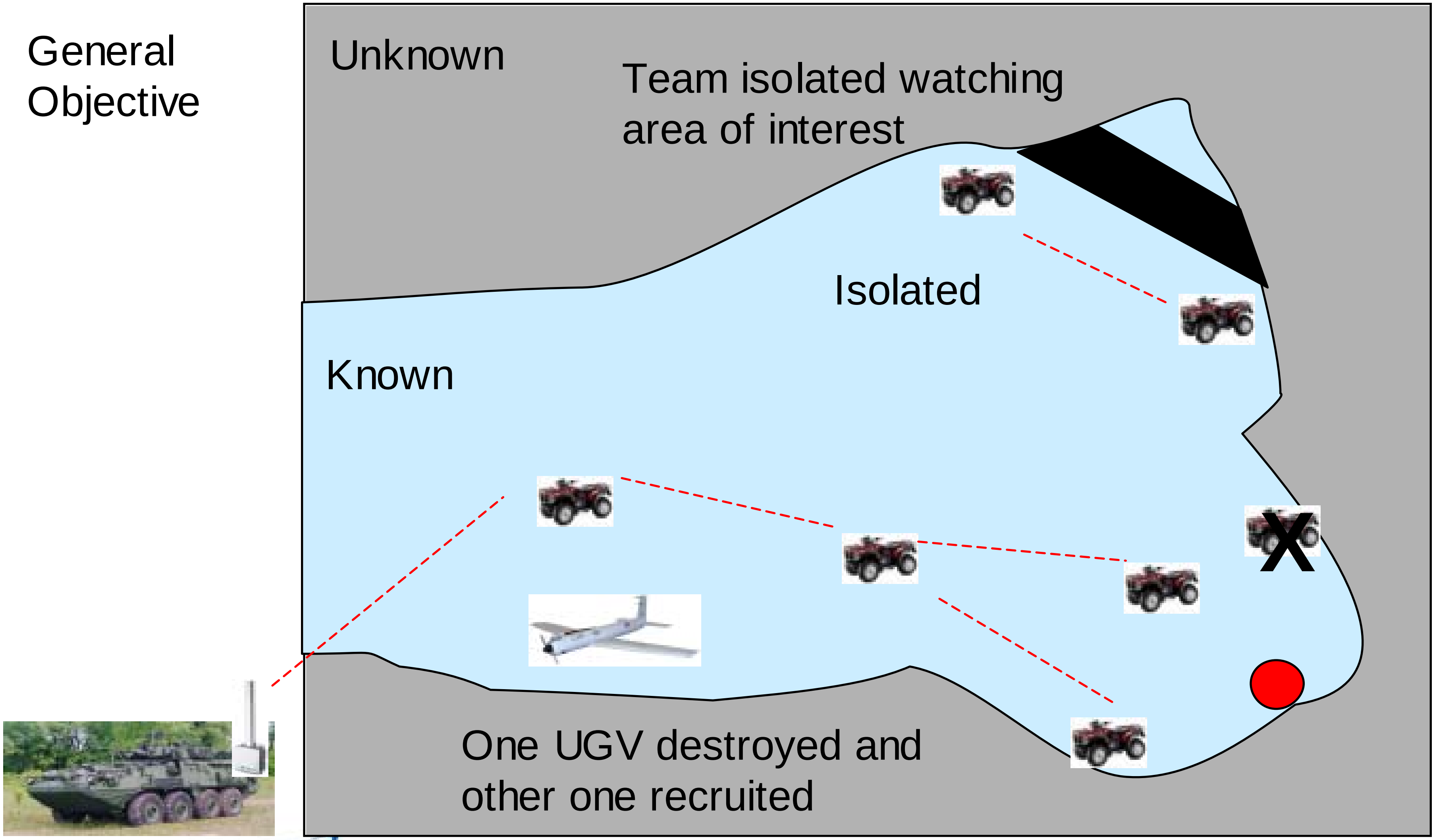


Mission Scenario Slide 3



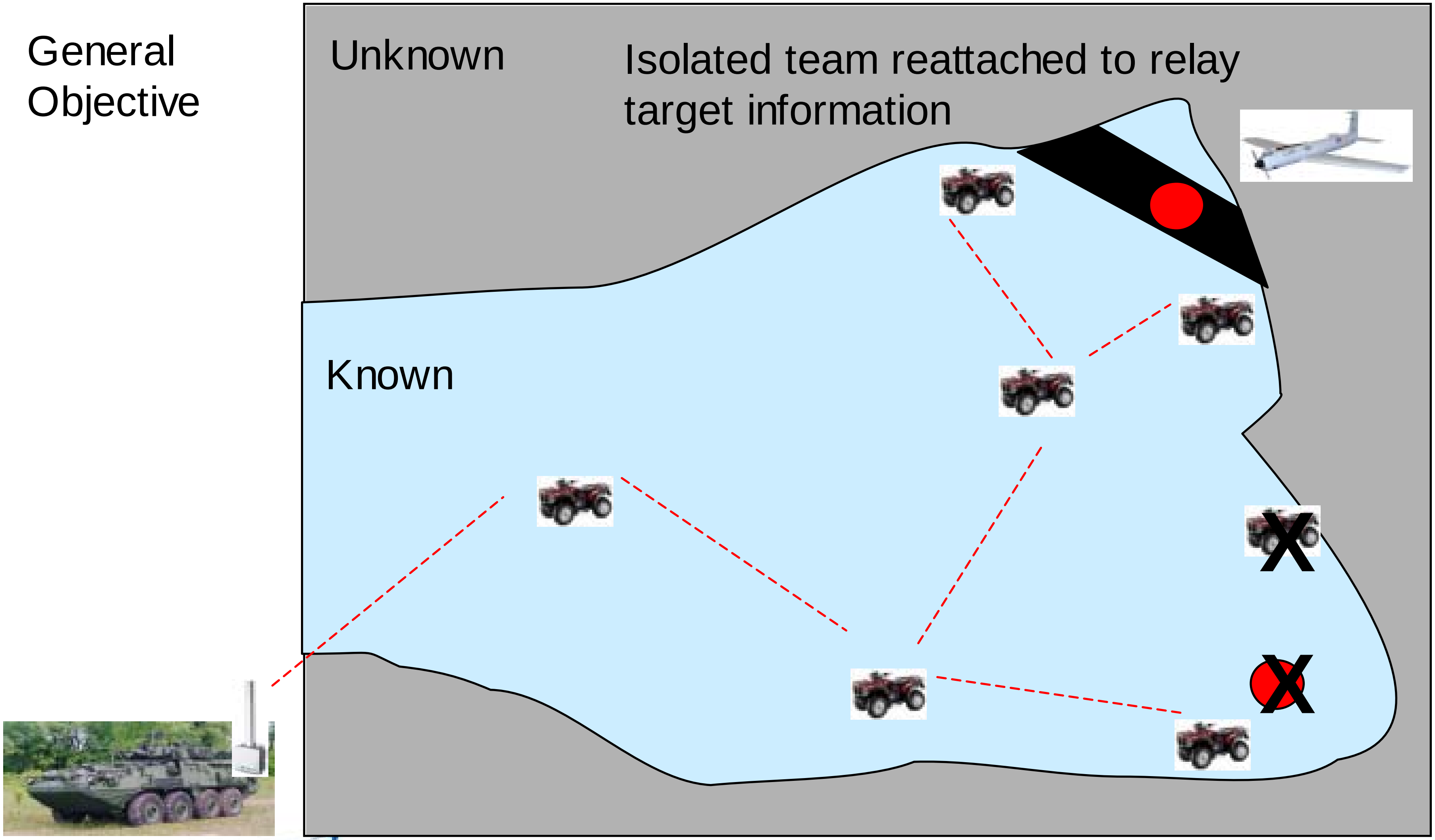
Mission Scenario Slide 4

General Objective



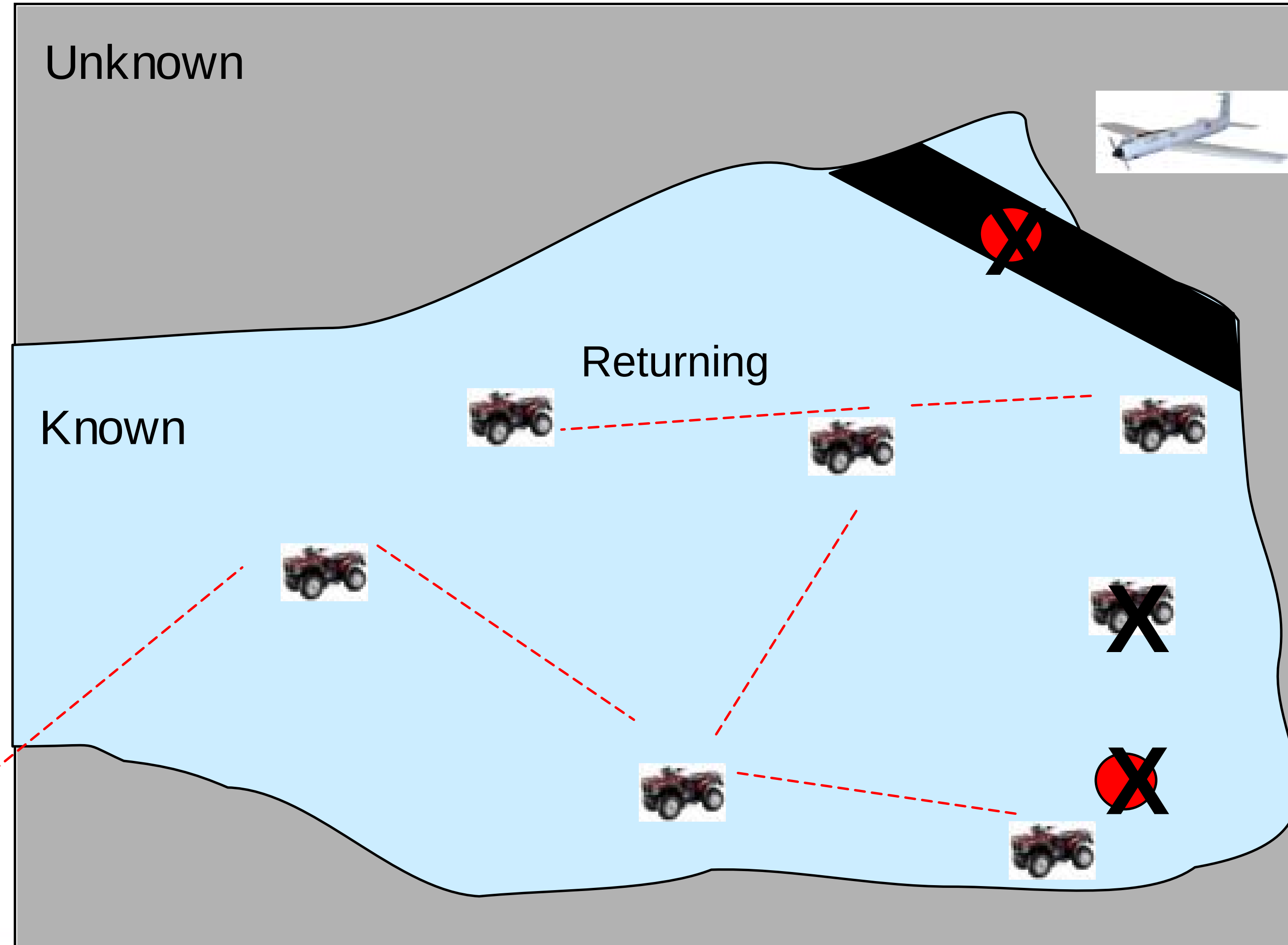
Mission Scenario Slide 5

General
Objective



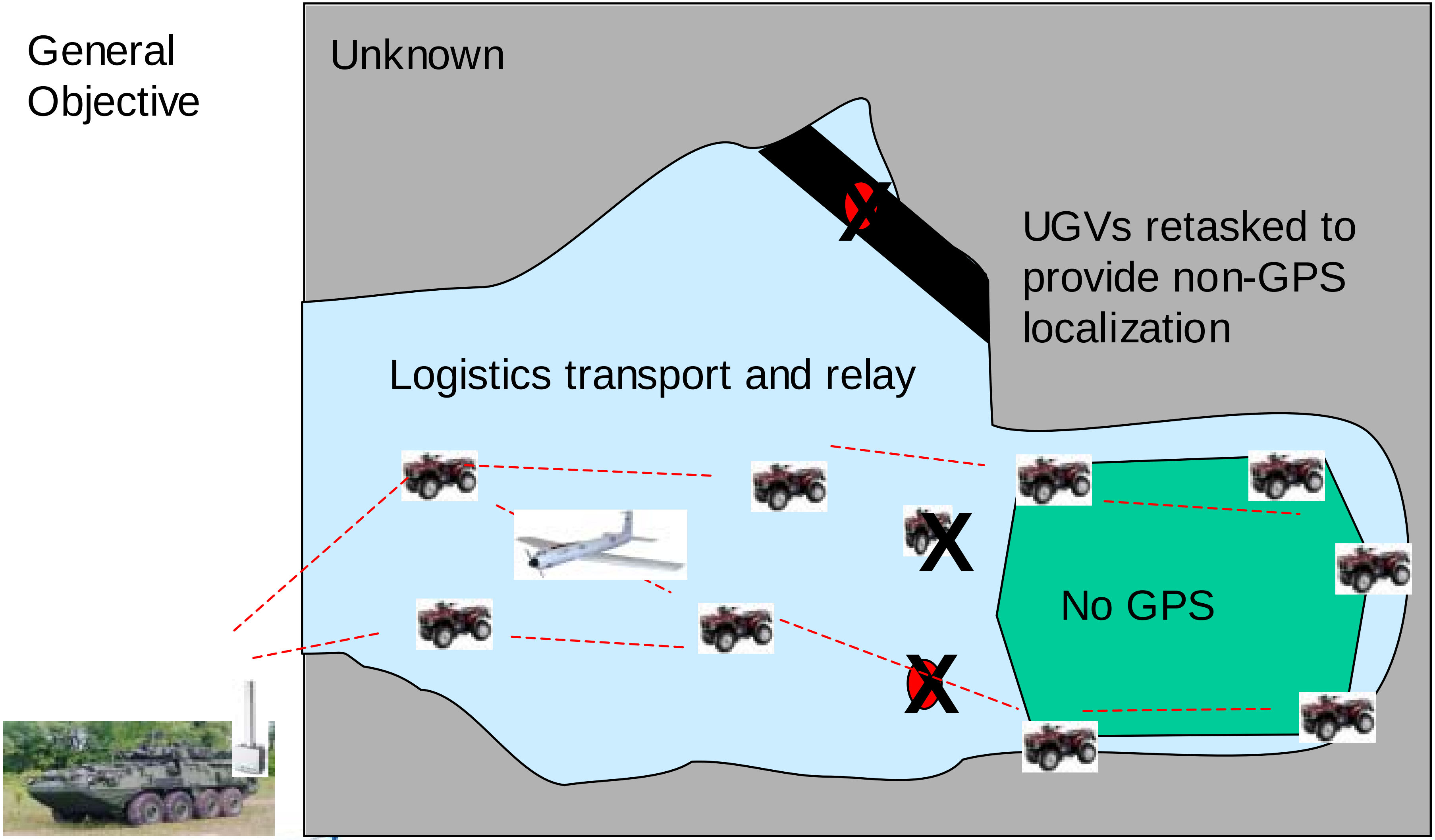
Mission Scenario Slide 6

General Objective



Mission Scenario Slide 7

General Objective



Expectations revisited

- Autonomy in real environments with broad application range will be a great challenge
- Many grand plans are in place
- Common falter points:
  - No unified algorithmic approach
  - No informal asynchronous operation
  - Poor scaling up of algorithms
  - Awkward integration
- Faster computers will help but new algorithms and theory needed
- Balance *evolutionary* head start with online learning
- General purpose autonomous machines many years away
- Useful niche purpose and sub systems realizable

Conclusions

- DRDC's Autonomous Intelligent Systems is growing
- Technology Investment Strategy is providing:
  - Mandate for research
  - New scientist (11) and support hires (7)
- Program and TIF funds support AIS
- DRDC wide effort
- Work with US, TTCP and NATO
- DRDC has a substantial, sustained and focused effort
- ALS has tangible demo that will ground expectations in reality

Terminator or Toonces

The cat who can drive
– just not very well

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