4D/RCS: AN AUTONOMOUS INTELLIGENT CONTROL SYSTEM FOR ROBOTS AND COMPLEX SYSTEMS OF SYSTEMS

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PURPOSE OF PRESENTATION

- Describe an autonomous intelligent control system architecture
- Suitable for controlling individual or collective robots or complex systems of systems
- For military or civil applications
- 4D/RCS: 3 dimensions of space and 1 of time in a Real-time Control System (RCS)
- Developed over last 30 years by the Intelligent Systems Division (ISD) of the National Institute of Standards and Technology (NIST), an agency of the U.S. Department of Commerce
- More than $125 million invested by U.S. government, not including an additional $250 million for application as Autonomous Navigation System (ANS) in Army’s Future Combat System (FCS)
BACKGROUND

- **4D/RCS**
  - Originated in early work by Dr. James Albus on neuro-physiological models and adaptive neural networks
  - Originally designed to control manufacturing facilities, where the entire manufacturing facility might be considered to be a distributed robot with strategic planning at the top levels of the control hierarchy, work cells in the middle levels, individual machine tools at the lower levels, and individual servos at the bottom level
  - Since modified and adapted for robotic vehicles, especially for various robotic ground vehicles where it was successfully demonstrated driving robotic ground vehicles autonomously on roads and cross-country
EXTENSION TO COMPLEX SYSTEMS

- **4D/RCS**
  - A framework in which sensors, sensor processing, databases, computer models, and machine controls may be linked and operated such that the system behaves as if it were intelligent.
  - Can be designed to permeate a system or a system of systems, where the systems may be fully autonomous, or human supervisors can interface with the 4D/RCS in a number of ways via communications and command and control links.
  - Can also interact with distant databases, machines, and control centers.
  - Can serve as a decision tool for decision-makers, for complex systems of systems.
EXTENSION: FUTURE COMBAT SYSTEM (FCS)

Estimated Development Cost By 2014: $250 Billion
WHAT ARE ARCHITECTURES AND SYSTEMS?

- **Architecture:**
  - The fundamental organization of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolution [IEEE Standard 1471-2000]

- **System:**
  - A set of variables selected by an observer, where a variable may be defined as a measurable quantity which at every instant has a definite numerical value - a quantity which, for example, can be represented by a measuring device such as a ruler or a gas gauge (or a subjective evaluation)
  - Anything that has parts (an observer may define a system to be whatever is convenient for a particular purpose)
WHAT ARE COMPLEX AND CYBERNETIC SYSTEMS?

- **Complex system:**
  - System in which there are many variables and interconnections among variables (called *detail complexity*), or where cause and effect are not close in time and space and obvious interventions do not produce the expected outcomes (called *dynamic complexity*).
  - System with the potential to evolve over time, with subsystems having emergent properties that can be described only at higher levels in the system than those of the subsystems.

- **Cybernetic system**
  - Systems which have negative feedback and are therefore controllable; often consisting of organisms and machines.
The question is not how smart a robot should be, but how dumb can it be and still do its job?
WHAT IS INTELLIGENCE?

- **Pragmatic definition of intelligence:** an *intelligent system* is a system with the ability to act *appropriately* (or make an appropriate choice or decision) in an uncertain environment
  - An *appropriate* action (or choice) is that which maximizes the probability of successfully achieving the *mission goals* (or the *purpose* of the system)
- Intelligence need not be at the *human* level
WHAT IS INTELLIGENCE?

Three useful corollary definitions of intelligence:

- **Reactive intelligence (adaptation)**
  - Based on an autonomic sense-act modality
  - Ability of the system to make an appropriate choice in response to an immediate environmental stimulus (i.e., a threat or opportunity)
  - Example: it is raining and the system is getting wet, so it seeks shelter

- **Predictive intelligence (learning)**
  - Based on memory
  - Ability to make an appropriate choice for events that have not yet occurred but which are based on prior events
  - Example: it is very cloudy and the system infers that it will likely rain soon, so it decides to seek shelter before it rains

- **Creative intelligence (invention)**
  - Based on learning and the ability to cognitively model and simulate
  - Ability to make appropriate choices about events which have not yet been experienced
  - Example, it takes too much time and energy for the system to seek shelter every time it rains or threatens to rain, so it invent an umbrella to shield it from the rain (the system can imagine that the umbrella, which never before existed, will protect it from the rain)
WHAT IS LEARNING?

- Learning: the acquisition of knowledge, skill, ability, or understanding by study, instruction, or experience, as evidenced by achieving growing success (improved behavior), with respect to suitable metrics, in a *fixed* environment

- Learning takes place when the system’s behavior *increases the efficiency* with which data, information, and knowledge is processed so that desirable states are reached, errors avoided, or a portion of the system’s environment is controlled
WHAT IS ADAPTATION?

- Adaptation: A change in behavior (or structure) in response to a changed environment
  - Able to maintain critical or essential variables within physical (or physiological) limits (e.g., homeostasis)
  - Where the changed behavior (or structure) increases the probability that the system can achieve its function or purpose (e.g., maintain homeostasis) by adjusting to the new or changed environment

Learning – fixed environment
Adaptation – changed environment
WHAT IS WISDOM?

- Many projects to develop machine learning and intelligence – but none yet for machine wisdom
- The original meaning of the word *philosophy* is “love of (or search for) *wisdom*”
  - A perception of the relativity and relationships among things
  - An awareness of wholeness that does not lose sight of particularity or concreteness, or of the intricacies of interrelationships
  - The ability to filter the inessential from the essential
  - The ability to recognize that which is significant amongst the detail – *to see the forest as well as the trees*

Knowledge involves aggregating facts; wisdom lies in disaggregating facts

"Things should be made as simple as possible, but not any simpler."
- Albert Einstein
AUTONOMOUS INTELLIGENCE: DOD GOAL
WHAT IS AUTONOMY?

- Still being defined
- ALFUS (Autonomy Levels For Unmanned Systems) Working Group
  - Managed by the Army Research Lab (ARL) and the National Institute of Standards and Technology (NIST)
  - Since 2003, meets at various U.S. locations

<table>
<thead>
<tr>
<th>autonomy levels</th>
<th>MC</th>
<th>ED</th>
<th>HRI</th>
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<tbody>
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<td>10</td>
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MC: mission complexity, ED: environmental difficulty, HRI: human-robot interaction
WHAT IS AUTONOMY?

- **ALFUS**: Focusing on three key variables: Mission Complexity, Environmental Difficulty, and Human Interface.
<table>
<thead>
<tr>
<th>Level</th>
<th>Name</th>
<th>Description</th>
<th>Example</th>
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<tbody>
<tr>
<td>0</td>
<td>Human Operated</td>
<td>All activity within the system is the direct result of human-initiated control inputs. The system has no autonomous control of its environment, although it may have information-only responses to sensed data.</td>
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<td>1</td>
<td>Human Assisted</td>
<td>The system can perform activity in parallel with human input, acting to augment the ability of the human to perform the desired activity, but has no ability to act without accompanying human input</td>
<td>Automobile automatic transmission and anti-skid brakes.</td>
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<td>2</td>
<td>Human Delegated</td>
<td>The system can perform limited control activity on a delegated basis. This level encompasses low-level automation that must be activated or deactivated by a human input and act in mutual exclusion with human operation.</td>
<td>Automatic flight controls, engine controls</td>
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<td>3</td>
<td>Human Supervised</td>
<td>The system can perform a wide variety of activities given top-level permissions or direction by a human. The system provides sufficient insight into its internal operations and behaviors that it can be understood by its human supervisor and appropriately</td>
<td></td>
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<tr>
<td>4</td>
<td>Mixed Initiative</td>
<td>Both the human and the system can initiate behaviors based on sensed data. The system can coordinate its behavior with the human's behaviors both explicitly and implicitly. The human can understand the behaviors of the system in the same way that he und</td>
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<tr>
<td>5</td>
<td>Fully Autonomous</td>
<td>The system requires no human intervention to perform any of its designed activities across all planned ranges of environmental conditions.</td>
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Six levels (four Regions) stated in terms of degree of operator interaction (adopted from the Naval Studies Board report on ONR UCAV Program, Summer 2000)

Required Operator Control Power per Vehicle

Level of Autonomy per Vehicle

1. Human Operated
2. Human Assisted
3. Human Delegated
4. Human Supervised
5. Mixed Initiative
6. Fully Autonomous

Region Requiring Intelligent Aiding

UCAV-N Design Space
Dynamic Re-plan, Auto Survival Response, Contingency Response, Target of Opportunity, Multi-Agent Collaboration, Mixed-Initiative Behaviors

Manual
Automated
Semi-Autonomous
Autonomous

100% Human
100% Machine

Min Level for Teleoperated Control
Auto Pilots, Auto IFF, Automatic Modes
Auto Route, Auto Target Track, Auto Land, Scripted Skills

TUAV
VTUAV
EXAMPLE AUTONOMY TAXONOMY (NORTHROP-GRUMMAN)

**UCAV System Level of Autonomy**

- **Deliberate Operations**
  - Computer executes commands initiated by operator. (Computer may provide and/or recommend decision alternatives to operator)

- **Aided Operations**
  - Computer generates decision alternatives and recommends one to carry out — but only with operator approval. Operator may select alternative option

- **Autonomous Operations**
  - Computer generates decision alternatives and a preferred option to execute and informs operator in time for intervention

- **Adaptive Operations**
  - Computer performs all aspects of decision-making and informs operator after the fact, if required, per preplanned criteria or operator request

**Human-System Interaction Approach**

- Low Autonomy
- Manual Control (Sheridan 1-2)
- Consent Based Control (Sheridan 3.5)
- Supervisory Control
- Executive Control (Sheridan 9-10)

- High Autonomy

**Operator Control Level**

- Low Autonomy
- UCAV System Level of Autonomy
EXAMPLE AUTONOMY TAXONOMY

1) System offers no assistance – operator must do everything
2) System offers a complete set of action alternatives to operator
3) System narrows the action alternatives to a few
4) System suggests a selection, and
5) System executes a selection if operator approves, or
6) System allows operator a restricted time to veto before automatic execution, or
7) System executes automatically, then necessarily informs operator, or
8) System informs operator after execution only if operator asks, or
9) System informs operator after execution - if system decides to
10) System decides everything and acts autonomously, essentially ignoring the human
AUTONOMOUS INTELLIGENT CONTROL

- Many prospective autonomous intelligent control system architectures
- NIST 4D/RCS most advanced
  - 30 years development and $100 million invested
  - Demos I, II, III, and many other successful demonstrations
- Used by GDRS for FCS Autonomous Navigation System (ANS)
BASIC INTELLIGENT SYSTEM

Perception establishes correspondence between internal world model and external real world.

Behavior uses world model to generate action to achieve goals.

OODA LOOP:

- Orient
- Decide
- Act
- Observe

Perception

World Model

Behavior

Observing

Deciding

Acting

Sensing

Real World

Goal
4D/RCS ARCHITECTURE

- Battalion Formation
- Platoon Formation
- Section Formation
- Objects of attention

OODA

- Surrogate Battalion
- Plans for next 24 hours
- Surrogate Platoon
- Plans for next 2 hours
- Surrogate Section
- Plans for next 10 minutes
- Vehicle
- Plans for next 50 seconds
- Task to be done on objects of attention

Subsystem

- 5 second plans
- Subtask on object surface
- Obstacle-free paths

Primitive

- 0.5 second plans
- Steering, velocity

Servo

- 0.05 second plans
- Actuator output

Sensors and Actuators

Operational Interface
A 4D/RCS COMPUTATIONAL NODE
4D/RCS: KNOWLEDGE IS CENTRAL
A 4D/RCS COMPUTATIONAL NODE

Planning Loop

Feedback Loop

4D/RCS node

Planning

Execution
CONTROL ARCHITECTURES

- Three major types: hierarchical (deliberative); reactive; hybrid (deliberative/reactive)
In addition to deliberative and reactive behaviors, an intelligent control system could also be **reflective**

- Able to monitor and alter its behavior (i.e., its critical variables) to better adapt
- A meta-control system controls the intelligent control system
Numerous journal articles, reports, and conference papers
Extensive software library: http://www.isd.mel.nist.gov/projects/rcslib
Intelligent vehicle technology is advancing more rapidly than most people -- including many experts -- are aware. A fundamental understanding of how to integrate perception, world modeling, knowledge representation, task decomposition, planning, and control for autonomous vehicles is emerging. The sensor technology and computing power required to achieve high performance autonomous mobility are becoming available. Both military and commercial organizations are making large investments in intelligent vehicle systems.

This book describes the 4D/RCS reference model architecture that provides a theoretical foundation for designing, engineering, integrating, and testing intelligent vehicle systems. This reference model embodies the experience of more than three decades of research and development of intelligent systems in many application domains. The authors show how the 4D/RCS model is being applied to the domain of autonomous mobility.

This book presents a comprehensive overview and systematic engineering approach for research and development of autonomous mobility systems. It can serve as a textbook or reference for advanced courses in artificial intelligence, robotics, and intelligent vehicle systems.