Intelligent Control and Tactical Behaviors for Unmanned Ground Vehicles

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Basic Intelligent System

**OODA loop**

- Perception
- World Model
- Behavior
- Real World
- Action

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

**Behavior** uses world model to generate action to achieve goals
4D/RCS Reference Model Architecture for Unmanned Vehicle Systems

Adopted by GDRS for FCS Autonomous Navigation System
Adopted by TARDEC for Vetronics Technology Integration

- Hierarchical structure of goals and commands
- Representation of the world at many levels
- Planning, replanning, and reacting at many levels
- Integration of many sensors stereo CCD & FLIR, LADAR, radar, inertial, acoustic, GPS, internal
Attributes of 4D/RCS

- Combines AI with control theory
- Hierarchical representation of tasks, space, & time
- Combines deliberative with reactive at many levels
- Depends strongly on sensing and perception
- Supports a rich dynamic world model at many levels
- Integrates prior knowledge with current observations
- Models functional architecture of the human brain
- Addresses the full range of human behavior
- Is mature with engineering tools and software libraries
Intelligent System Architecture

4D/RCS Reference Model

OPERATOR INTERFACE

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

Surfaces
- Attention
- Communication
- Mission Package
- Locomotion

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

Points
- 0.5 second plans
- Steering, velocity

SERVO
- 0.05 second plans
- Actuator output

SENSORS AND ACTUATORS
A 4D/RCS Computational Node

4D/RCS

RCS Node

SENSORY OUTPUT

PERCEIVED OBJECTS & EVENTS

VALUE JUDGMENT

PLAN

EVALUATION

PLAN RESULTS

BEHAVIOR GENERATION

SENSOR INPUT

OBSERVED INPUT

PREDICTED INPUT

KNOWLEDGE DATABASE

UPDATE

Situation Evaluation

To Higher and Lower Level World Modeling

STATUS

COMMANDED ACTIONS (SUBGOALS)

COMMANDED TASK (GOAL)

OPERATOR INTERFACE

PEER INPUT OUTPUT
Knowledge is Central
Forms of Representation

Iconic
- signals, images, maps (arrays)
- Support communication, geometry, and navigation
- Have range and resolution in space and time

Symbolic
- objects, events, classes (abstract data structures)
- Support mathematics, logic, and linguistics
- Have vocabulary and ontology

Links
- relationships (pointers)
- Support syntax, grammar, and semantics
- Have direction and type
MULTI-RESOLUTION MAPS

- Data flows up and down between the different maps
- Path planning occurs at each level

0.4 m grid
50 m wide

4 m grid
500 m wide

30 m grid
Terrain map
Sensory Processing

*Classification
  Compare group attributes with class prototype
  Set pointers that define class membership

Computation of Group Attributes
  e.g., size, shape, texture, motion
  Recursive estimation of group attributes

*Segmentation and Grouping
  Segment pixels that meet grouping criteria
  Set pointers that define grouping relationships

Focus Attention
  Direct sensors to region of interest
  Window and track interesting entities and events
Segmentation & Grouping

Spatial pixel patterns => Entities
Temporal signal patterns => Events

**Fundamental Problems:**
Any segmentation is a hypothesis. Needs confirmation.
2D images are ambiguous in range => infinite # of hypotheses

Segmentation criteria == Gestalt grouping hypotheses
  Proximity in space or time
  Similarity in brightness, color, shape, size, texture, etc.
  Symmetry, Smooth continuation

Bottom-up segmentation of optical images is notoriously poor.
Need to integrate top-down inputs
Classification

Fundamental Problem
Object classification depends on:
1. accurate segmentation and grouping
2. dimensionality of object attribute vector
3. number of pixels on target (> 100)

Optical images are high in resolution, but ambiguous in range. Therefore, segmentation is hard

Range images are low in resolution
Therefore, not enough pixels on target

Data fusion helps
High-level context helps more
LADAR is a Critical Break-Through

2D Color Image

3D Range Image

Range and slope are ambiguous
Segmentation is difficult

Enables transformation into geocoordinates
Next Generation LADAR
Intensity Image in the Woods
Geocoordinates Overhead View
High Resolution LADAR

.02 degree angular resolution
2 cm range resolution
5 x 80 degree field of view
Segmentation based on Fusion of Color & LADAR Images

James Albus
Tsai Hong
Mike Shneier
Gerry Cheok
Tommy Chang

National Institute of Standards and Technology
U. S. Department of Commerce
Color Segmentation

Road Edge Detection

Road Detection
Road edges from color image
Segment out everything to right and left of road edges
Segment out everything > 2 m above road and range > 70 m
Segment out road and points < 20 cm above road
Compute Attributes of Segmented Cars

Object 1
- Range = 41 m
- Closing speed = 2 m/sec
- Width = 176 cm
- Height = 128 cm

Object 2
- Range = 62 m
- Closing speed = 2 m/sec
- Width = 162 cm
- Height = 140 cm

Classify based on height, width, and closing speed
Image Processing of High Resolution Range Images

Human Detection in a Cluttered Environment at 50 meters

Jim Albus, Tsai Hong, Will Shackelford, Tommy Chang, Gary Haas
Three Mannequins
Segmentation based on Connected Components
Color Image Windowed by Humans Detected in Range Image
full res color face in bull rushes
color face in bull rushes
Classification requires pixels on target

Translates into resolution required at distance
Color Video Camera
25 m @ .02 deg/pix
~ human vision

~ 10,000 pixels
on human target
Current real-time LADAR
25 m @ .2 deg/pix

~ 100 pixels on human target
Current real-time LADAR
50 m @ .2 deg/pix

~ 25 pixels
on human target
Current real-time LADAR
100 m @ .2 deg/pix

~ 6 pixels on human target
High resolution LADAR
50 m @ .05 deg/pix
Non-real-time

~ 400 pixels on human target
High resolution LADAR
100 m @ .02 deg/pix
Non-real-time

~ 600 pixels on human target
LADAR Resolution Required to Recognize Human Form at Various Distances

<table>
<thead>
<tr>
<th>Distances</th>
<th>Resolutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 m</td>
<td>.2 deg/pix</td>
</tr>
<tr>
<td>50 m</td>
<td>.05 deg/pix</td>
</tr>
<tr>
<td>100 m</td>
<td>.02 deg/pix</td>
</tr>
</tbody>
</table>
4D/RCS Methodology for Tactical Behaviors

The ability to perform tactical behavior is the reason the Army is interested in robotics.

<table>
<thead>
<tr>
<th>Level</th>
<th>Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company</td>
<td>30 to 40</td>
</tr>
<tr>
<td>Platoon</td>
<td>8 to 10</td>
</tr>
<tr>
<td>Section</td>
<td>2 to 4</td>
</tr>
<tr>
<td>Vehicle</td>
<td>single</td>
</tr>
</tbody>
</table>

Manned/Unmanned collaboration
UGV/UAV/UGS collaboration

### 4D/RCS for FCS

- **Battalion**
  - Battalion HQ
  - Artillery
  - Armor
  - Logistics
  - 24 hr plans replan every 2 hr
  - 5 hr plans replan every 25 min
  - 1 hr plans replan every 5 min
  - 10 min plans replan every 1 min
  - 1 min plans replan every 5 s
  - 5 s plans replan every 500 ms

- **Company**
  - IndirectFire
  - DirectFire
  - AntiAir
  - UAV C2
  - Manned C2
  - UGS C2
  - 50 ms plans output every 5 ms
  - 5 s plans replan every 50 ms
  - 10 min plans replan every 1 min
  - 1 hr plans replan every 5 min
  - 5 hr plans replan every 25 min
  - 1 hr plans replan every 1 min
  - 5 s plans replan every 500 ms

- **Platoon**
  - UA
  - UARV
  - UGV Scout
  - Mobility
  - 1 min plans replan every 5 s
  - 5 s plans replan every 500 ms
  - 50 ms plans output every 5 ms

- **Section**
  - RSTA
  - Communications
  - Weapons
  - Sensors and Actuators

- **Vehicle**
  - Gaze
  - Select
  - Focus
  - Pan
  - Tilt
  - Iris
  - 500 ms plans replan every 50 ms
  - 50 ms plans output every 5 ms

- **Subsystem**
  - Driver
An Example Scenario

A Light Cavalry Troop receives a command to perform a tactical road march to an assembly area.

This results in a command to a Scout Platoon to perform a route reconnaissance of the road.

The scout platoon is composed of three sections, each containing three manned HMMWVs, one unmanned ground vehicle (UGV), and one unmanned aerial vehicle (UAV).
A Section Scenario

Scout section is conducting a route reconnaissance

HMMWV reconnoitering the right flank comes upon an unexpected water obstacle

Center HMMWV discovers a bridge

The two vehicle commanders report their findings to the section leader

The section leader then might command the manned vehicles to take up overwatch positions for near-side security

The section leader also commands the UAV to look for a route around the water obstacle. UAV sends hi-resolution color images data back to the section leader for manual viewing, and/or by scanning the ground with a LADAR to assess the topography.

Once a potential by-pass to the marsh is located, the UAV is commanded to search the far side of the marsh and the region beyond the next terrain feature for evidence of enemy forces.

UGV might then be commanded to proceed through the bypass and establish an overwatch position on the far side of the next terrain feature.

The UGV path can be automatically generated from the data returned from the UAV and approved by the section leader before being executed.

Once the UGV is set in position, the UAV continues scanning for enemy activity further along the route.

Manned elements perform manual reconnaissance of the marsh by-pass, and/or assess the load carrying capacity of the bridge.
Task Decomposition Tree (Route Reconnaissance Example)

Hierarchical Organization of Agent Control Modules

Capture Behavioral Knowledge

Task Analysis to Create Task Decomposition Tree

STEP 1

MAP to Agent Architecture

STEP 2

Hierarchical Organization of Agent Control Modules

STEP 3

MAP Task Decisions to State-Tables

STEP 4

Determine Antecedent World States

STEP 5

Identify Objects and Their Relevant Attributes

STEP 6

Determine Sensor Processing Requirements and Resolutions

SENSORY PROCESSING

WORLD MODEL KNOWLEDGE

BEHAVIOR GENERATION

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Input Conditions

Output Conditions

PLAN STATE-TABLE

ConductReconToCom...

4D/RCS Node

Result

Behavior Generator

Task Decomposition Tree

Vehicle | PLAN SELECTION

Saturated Ground

(Executing)

(ReconToRoute)

World States

Situations

Objects & Attributes

7.5' Bulrushes - tall tan-to-green stems, with dark brown cylindrical seed heads that explode into white down, long flat green sword shaped leaves, cattails.

6-18' LongLeaGrasses - very flat, long green leaves/purple/gray/yellow flowers.

6-48' Sedges - triangular tan/green stem plants, papyrus, narrow green to tan grass-like leaves, spikes of inconspicuous tan-to-yellow-to-white flowers.

1-6' Reeds - tall, woody, thin, round, hollow jointed (tan-to-green) stem plants, long narrow green blade leaves, large fluffy particles (elagated clusters of tan/white/purple flowers)

3 cm

0.9 to 2.7m

3 cm

2.4 cm

0.9 to 2.7m

2.4 cm

3 cm

Determine World Processing Request and Resolutions

Object Features and Attributes

Segmented Groupings

Color Cameras, LADAR, Radar, Stereo FLIR Nav

Sensory Processing

World Knowledge

Knowledge Database

Value Judgement

World Model

Behavior Generator

Agent Control Modules

Domain Experts

Vehicle | Tactically Assess Water Feature

Vehicles

(

Conduct

Route Recon

PrepareFor

RoadMarch

FollowPlatoon

ToAssemblyArea

Secure

A ...

... nPath

Cross

Ford

Scan Area

For Enemy

MoveTo

Water

ShiftTo

4WhLo

MoveTo

Opposite

Bank

ShiftTo

4WhHi

Dry

Brakes

3 cm

0.9 to 2.7m

3 cm

2.4 cm

3 cm

2.4 cm

3 cm

2.4 cm
TASK ANALYSIS to Create Task Decomposition Tree

STEP 1

DOT Driving Manuals and ARMY Field Manuals

Domain Experts

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Task Vocabulary at Each Echelon

- **ConductRoadMarchToAnAssemblyArea(AA)**
  - **Conduct RouteRecon**
  - **PrepareFor RoadMarch**
  - **FollowPlatoon ToAssemblyArea**
  - **PrepareDetailed MovementPlans**
  - **Secure AssemblyArea**
  - **Organize AssemblyArea**
  - **MoveInto MarchFormation**
  - **Execute RoadMarch**
  - **Support MarchColumn**
  - **Execute Sched. Halt**

**Top Echelon**
- **SetupMarch ColumnOrg**
- **FormRoad MarchOrg**
- **PlanRoute, ControlPoints**
- **Conduct RouteRecon**

**Middle Echelon**
- **SetupSections, Formations, MoveTechniques**
- **DeployTo StartPoint**
- **Conduct LeftFlank RouteRecon**
- **Conduct RightFlank RouteRecon**
- **Conduct MainRoute Recon**
- **Locate&Secure ObstacleBypass**
- **Conduct Obstacle Recon**
- **MoveTo ControlPoint**
- **Conduct AmbushSite Recon**
- **Preform Traveling Overwatch**
- **BoundTo Overwatch**
- **Evaluate&Classify Obstruction**
- **SetupShort DurationOP**

**Bottom Echelon**
- **MoveInto Formation**
- **MoveTo ControlPoint**
- **Locate WaterBypass**
- **Perform Ford Recon**
- **Ford Water Obstacle**
- **Secure Area**
- **MoveTo Cover/Concealed Position**
- **Overwatch Section**
- **Assess FordTerrain**
- **ScanArea ForEnemy**
- **Cross Ford**
- **MoveTo Position**
- **Scan Path**
- **MoveTo Water**
- **ShiftTo 4WhLo**
- **MoveTo Opposite Bank**
- **ShiftTo 4WhHi**
- **Dry Brakes**

**Second Echelon**
- **Scan Path**
- **MoveTo Water**
- **ShiftTo 4WhLo**
- **MoveTo Opposite Bank**
- **ShiftTo 4WhHi**
- **Dry Brakes**

**First Echelon**
- **Troop Commander - Input Command**
- **Platoon Leader - Input Commands**
- **Section Leader - Input Commands**
- **Squad/Vehicle - Input Commands**
- **Mobility - Input Commands**
- **Primitive/Trajectory - Input Commands**
Agent Architecture
Determine Transition Conditions
Identify Objects and Attributes
Determine Sensor Requirements

SENSORY PROCESSING

IDENTIFY OBJECTS and THEIR RELEVANT ATTRIBUTES

STEP 5

WORLD MODEL KNOWLEDGE

STEP 6

DETERMINE ANTecedent WORLD STATES

STEP 4

DETERMINE SENSOR PROCESSING REQUIREMENTS AND RESOLUTIONS

STEP 3

world states

world states

situation

situation

WORLD STATES

Situations

World States

Determine Sensor Requirements

STEP 5

IDENTIFY OBJECTS and THEIR RELEVANT ATTRIBUTES

STEP 6

DETERMINE SENSOR PROCESSING REQUIREMENTS AND RESOLUTIONS
CAPTURE BEHAVIORAL KNOWLEDGE

STEP 1: TASK ANALYSIS TO CREATE TASK DECOMPOSITION TREE

STEP 2: MAP TO AGENT ARCHITECTURE

STEP 3: MAP TASK DECISIONS TO STATE-TABLES

STEP 4: DETERMINE ANTECEDENT WORLD STATES

STEP 5: IDENTIFY OBJECTS AND THEIR RELEVANT ATTRIBUTES

STEP 6: DETERMINE SENSOR PROCESSING REQUIREMENTS AND RESOLUTIONS

SENSORY PROCESSING

WORLD MODEL KNOWLEDGE

BEHAVIOR GENERATION

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On-road Driving Analysis

NARRATIVE

Vehicle has detected Service Drive intersection and is now within the turning distance tolerance. This causes BG2 to send a TurnRight command to BG3 which will cause it to build goal paths along the lane segments forming the right turn onto Service Drive. This turn will be made at speed since the vehicle has the right-of-way at this intersection. This has been determined by the lack of detecting any traffic control devices for own lane of travel and the fact that Service Drive “tees” into South Drive which usually means that vehicles on South Drive will have the right-of-way.

BG2 will continuously update changes in the LaneSegments as measured by SP2 detecting road edges and surfaces. The curving road edges leading into Service Drive continue to be of interest and are, therefore, still in the BG3 ActiveObjectsTable and the SP2 ObjectsOfAttention list.

BG3 will continuously adapt the goal path to the LaneSegment changes from BG2 by controlling the real-time trajectory vector to Steer and Speed Control in BG4.
RCS Methodology

This is a tedious process.

There are many tasks in the command library at each level.

There are many parameters for each task.

There are many objects that must be recognized.

There are many situations that must be understood.

But, the numbers are not infinite. They are, in fact, quite modest. (One of the advantages of hierarchies.)
Autonomous On-Road Driving Vehicle Echelon and Down

Estimated numbers:

~ 200 tasks
~ 100 parameters
~ 1000 transition conditions
~ 10,000 objects or events

Other skills may require similar numbers
Summary

4D/RCS Reference Model Architecture has a proven success record for intelligent control

4D/RCS Methodology provides a systematic approach to software engineering for tactical behaviors
4D/RCS Documentation

4D/RCS
Version 2.0
- NIST Report, 2002

Engineering of Mind
- Wiley, 2001

RCS Handbook
– Wiley, 2001

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 framework 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.

Editors
Raj Madhavan
Elena Messina
James Albus

NIST • Manufacturing Engineering Laboratory • Intelligent Systems Division
Conclusions

1. Useful autonomous on-road and off-road driving will be feasible by 2010

2. Human level performance in autonomous on-road and off-road driving will be feasible by 2020

3. Future Combat System will provide the rational and funding to build intelligent vehicle systems
Questions?