Mobile Robotics

Introduction

Carnegie Mellon
THE ROBOTICS INSTITUTE

Outline

- Taxonomy
- Applications and Markets
- Subsystems
- Architecture
- Mechanical Configuration
- Design Themes & Issues
- Summary

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Why do the scientists build them?

Why Use Robots?: Goals and Purposes

- Potentially use em wherever
  - an animal, human, or vehicle …
  - does useful work
- Why spend the money on Robots?
  - Better -> consistency, control over process
  - Faster -> more out, less in, 24 hour clock
  - Safer -> let robots take the risks (mining)
  - Cheaper -> “people drive like maniacs”
  - Access -> outer space, bloodstream

Means of Classification

- Physical characteristics and abilities
  - Segmented body, Pan Tilt, Active Suspension
  - Ackerman Steer, Differential Steer, Skid steer
- Capability level
  - Autonomy level
  - Speed
- Environments for which they are designed
  - Structured (indoor), vs unstructured (outdoor)
- The job they do
  - Move material A to B
  - Search for Life.

Physical Attributes of Mobile Robots

- Terrainability (Ability to negotiate terrain)
  - Indoor (2D) or Outdoor (3D)
  - affects complexity of world model and a lot more
- Type of Locomotion
  - Wheeled, Legged, Tracked, Serpentine
  - affects path mobility models in planning
- Type of Steering
  - Ackerman, Synchronous, Differential, Skid, etc.
  - affects mobility models in planning

(More) Attributes of Mobile Robots

- Body Flexibility
  - Unibody or Multi body, Flexible or Rigid body
  - affects complexity of perception data processing
- Shape
  - Simple or complex, Soup Can vs Insect-Like
  - dramatically affects complexity of obstacle avoidance during planning
- Lineage
  - Retrofitted or Custom vehicle
  - affects hardware development cost versus ease of programming.
- Medium of Transport
  - Land, Water, Fuel, Pipes, Air, Undersea, Space
  - affects mechanism for coordinated actuator control

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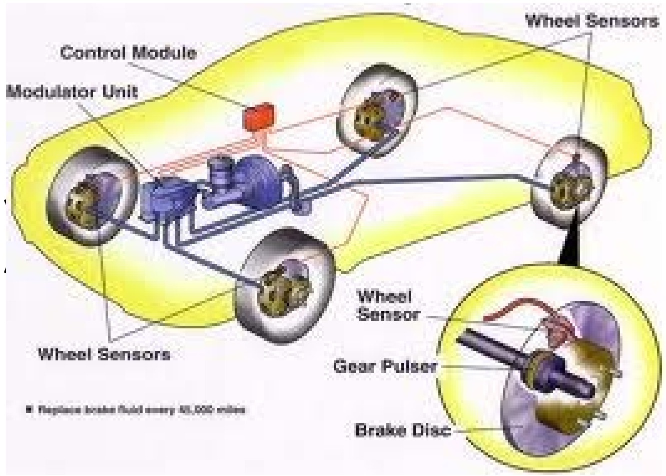
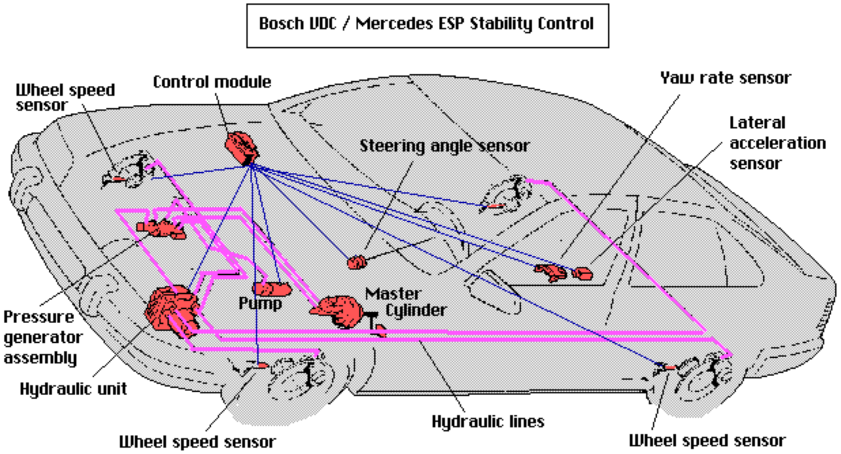
Robots at Work - Classes

- Automated Guided Vehicles
- Service Robots
- Cleaning and Lawn Care
- Social/Entertainment Robots
- Field Robots
- Surveillance and Exploration
- EOD
- Competition

Automotive Assistance

- ABS
- Yaw Stability Control (Slip)
- Roll Stability Control (Rollover)
- LDW
- Driver Monitor





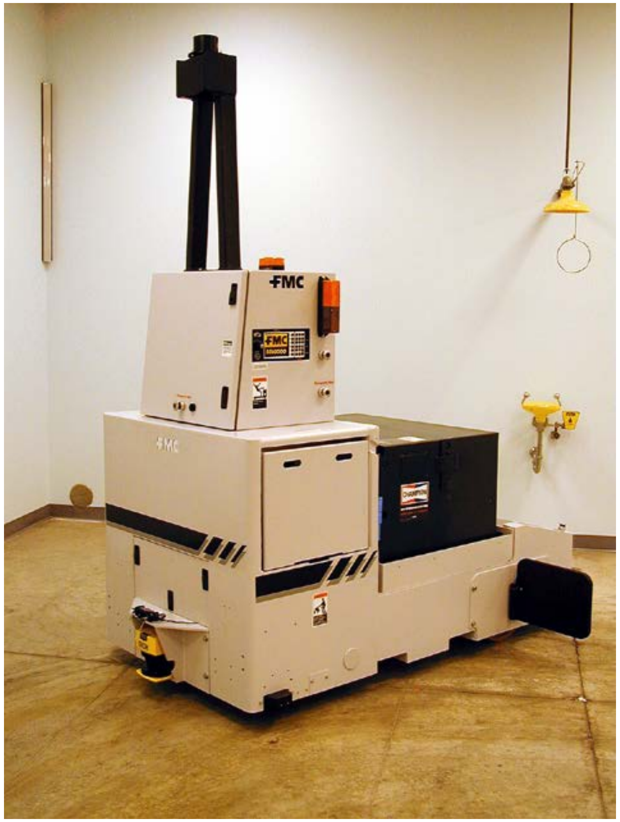
Automotive Assistance

LDW

Pedestrian Detection

Automated Guided Vehicles

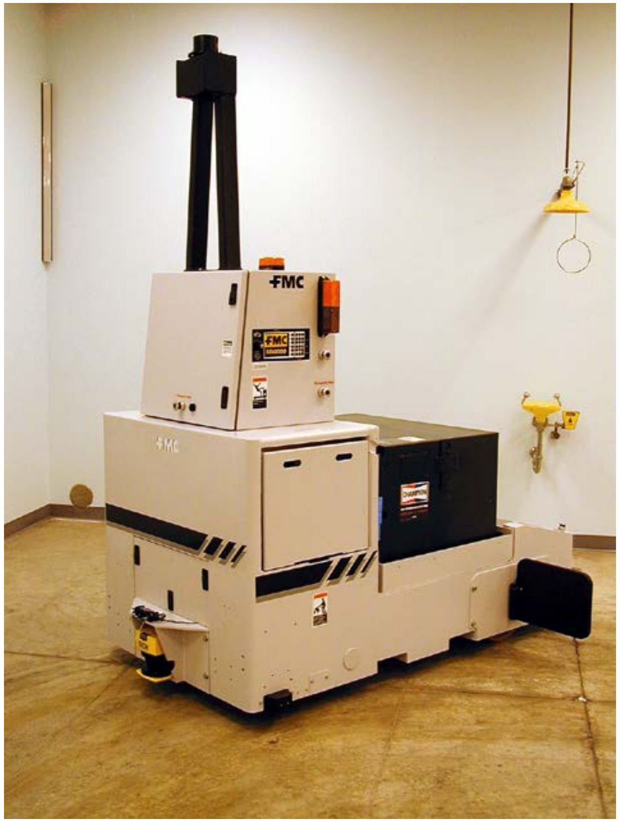
- Invented in 1950s.
  - Most developed market now.
  - Sales $300 Million in US in 2005 (RIA)
- Designed to move materials ("material handling").
- Work in factories, warehouses, shipping areas.
- Big users are auto parts, newspapers.
- Guidance
  - Wire – induce cross-track error
  - Inertial – plus magnets
  - Laser – plus reflectors



FMC Tug AGV
Chalfant, Pa

Automated Guided Vehicles

- Modern systems are controlled wirelessly
  - central traffic management computer.
  - allocates space to individuals
- Three configurations common:
  - Forked
  - Tug (tow/tractor)
  - Unit Load



FMC Tug AGV
Chalfant, Pa

Material Handling

Commercial
Solutions

Automated Guided Vehicles - Outdoors

Automated Straddle Carrier Brisbane Australia

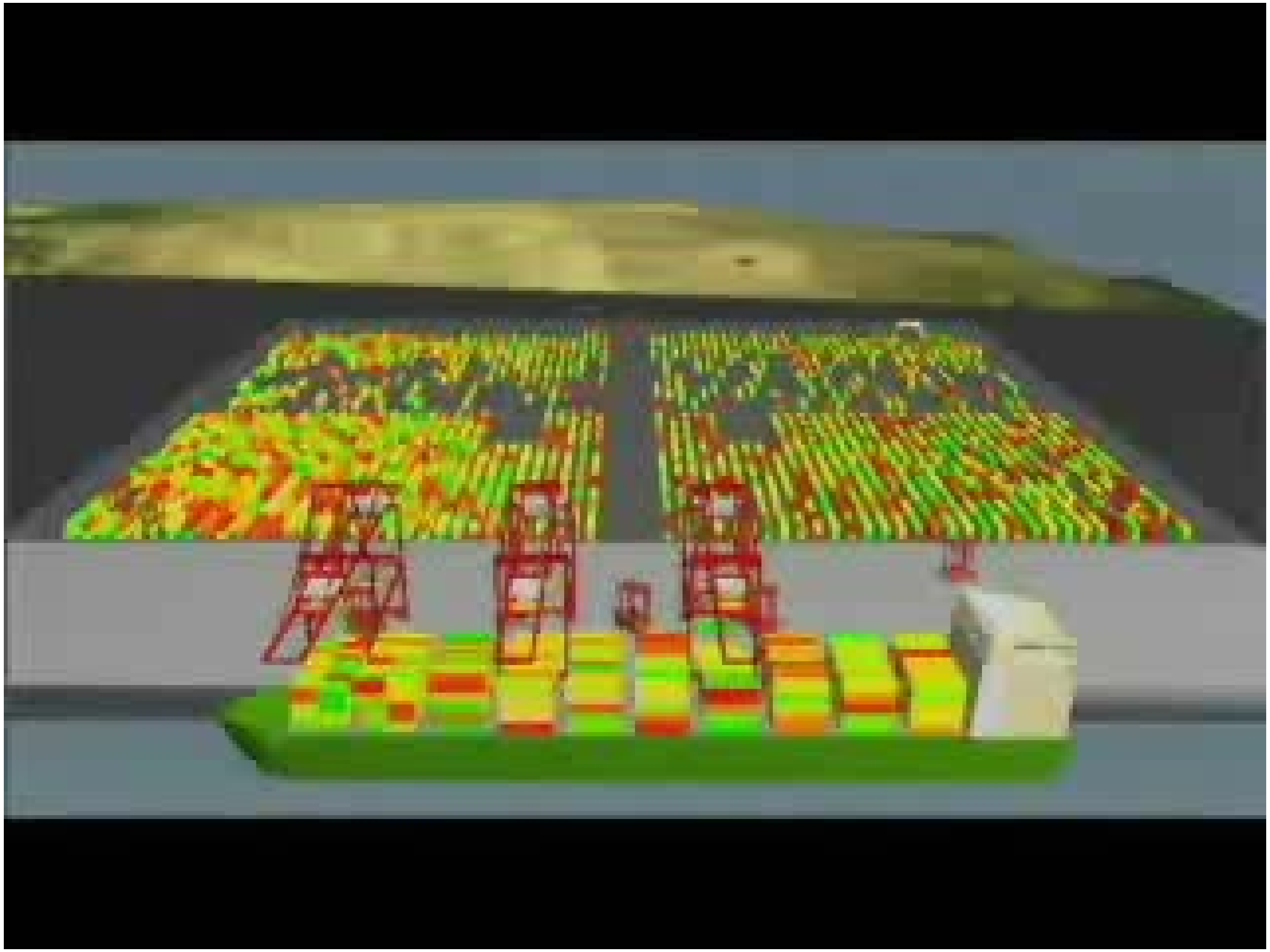
Ordinary Straddle Carrier Rotterdam, Netherlands

- 24-7 operation
- Shipyard staff thought there were people hiding inside until the power went out and
  - It kept on going in the dark !!!!!!

Port Automation

- Rotterdam, Brisbane, Singapore,

Straddle Carriers



AGVs for Order Picking

- Warehouses of the future are robots.
- Kiva inverts order picking.
- The racks come to the people.

AGVs FOR Order Picking

Service Robots - Information

- Do the kind of jobs that service industry employees do now.
  - Light material handling (schlepping mail, food, medications, magazines).
- Many involve intimacy with humans
  - Coping with crowds
  - Answering questions

EPFL Museum
Tour Guide
Lausanne, Switzerland

Service Robots - Information

Service Robots - Sales

- First Question when you enter Home Depot?
  - "Where do I find X"
- Robots can be mobile information kiosks
  - Show you Aisle 13
  - Print coupons
  - Suggestive selling
  - Chat about the ball game

Service Robots - Sales

Service Robots – Health Care

- Earliest use of robotics in Health Care in 1970s.
- Helpmate Robot used in US in 1990s.
    - Move bio samples, bio waste, linens, medical records.
    - About 50 were sold
- International Federation of Robotics says market for service and personal robots should reach $6.2 billion in 2005. ???

TRC HelpMate

Service Robots – Health Care

- Aethon is/was here in Pittsburgh.
    - Materials transport costs $3 million a year in labor.
    - RN's are involved too much in doing his.
- Robots rent for $1500 per month.

Aethon Corp. "Tug"
Pittsburgh, Pa

Service Robots – Health Care

- Intuitive Surgical formed for minimally invasive surgery > 12 years ago.
- $600 million revenue in 2007.
- 1,000 systems installed in hospitals worldwide.
- My sources say it does not work better than manual.
  - Patients are demanding it based on perception it is better..

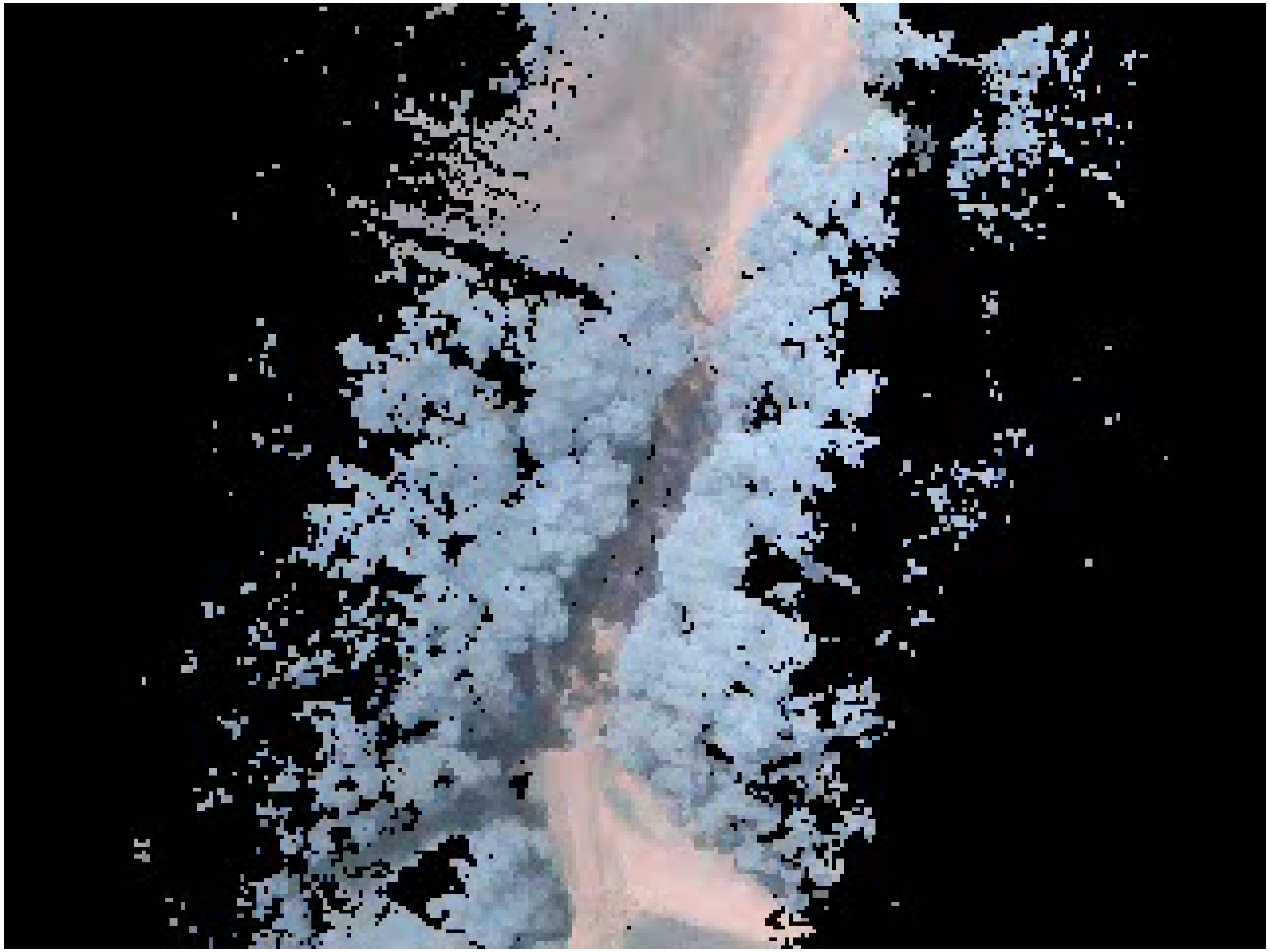

(a)
(b)

Service Robots – Health Care

Mapping / Metrology

- Traffic Maps
- Forestry Inventory
- Mining Process Monitoring
- Military

Mapping / Metrology



Service Robots – Security Guards

- A simple application.
  - Move around a building when there is (supposed to be) no one there.
  - Notify someone of any funny business.
- Denning finally gave up after about 10 years.

Robart

Denning

Service Robots – Cleaning

- Commercial versions used in airports, supermarkets, shopping malls, schools, factories, etc, for some time.
- Special tunnel cleaning car in Paris Metro deployed in 1999.

Windsor

Intellibot
Servus
Kent

Service Robots – Cleaning

- As of right now, household cleaning robots has made one professor super rich.
- As of Jan 2006, iRobot has sold 1.2 million Roomba or $95 million in sales.
  - About $150 each
  - Company IPO for $115 Million while still losing money in 2005.
- Electrolux Trilobite
  - Introduced in 1997
  - About $1500 each
    - Sonars, not bumpers give real obstacle avoidance.
    - Can map the area, not random.
    - Powerful vacuum

Roomba

Electrolux
Trilobite
2.0

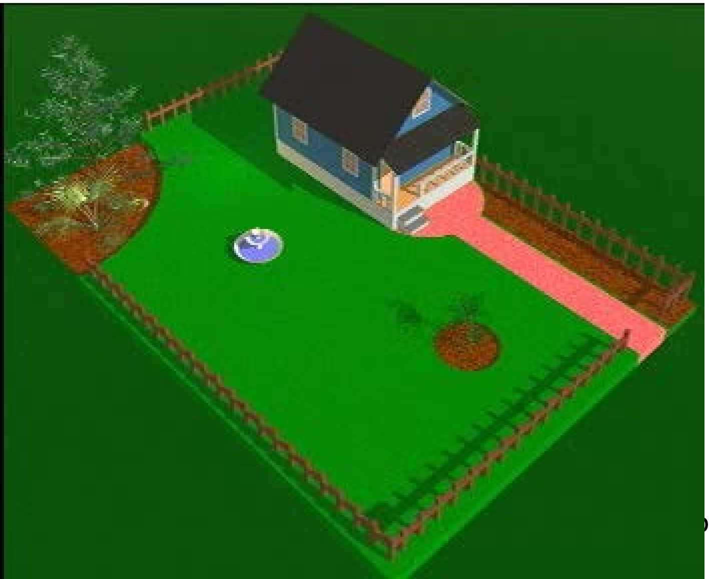
THE

Vacuum and Coverage

Service Robots – Lawn Care

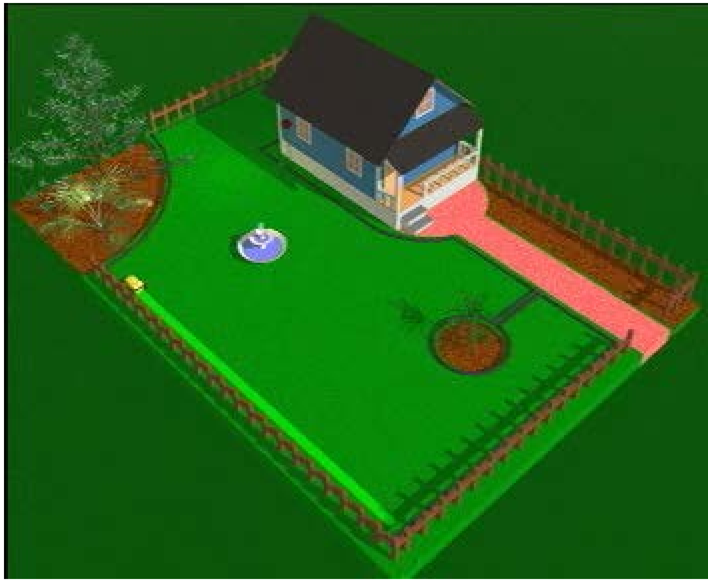
- Robotics Robomow.
  - $1196 as shown.
  - “It mows. You don’t”
  - Israeli company
- You specify perimeter.
- Raster scan coverage algorithm

Friendly Robots



← Setup

Mowing →



f Alonzo Kelly, CMU RI

Lawn Care

Social / Entertainment

- SONY has shipped 100,000 Aibos as of Sept 2005.
  - Cost down from $2500 to $850.
  - Chases balls
  - Wags its tail, rolls over, scratches itself
- Ah….Real dogs are free….

Sony QRIO

SONY Aibo

Social / Entertainment

Social / Entertainment

- Wowee Robsapiens
  - Hong Kong company
  - $100
- Walks, dances, does karate moves, pick things up, and throw them, explains
- Sold more than 2 million worldwide the first year.

Wowee RoboRaptor

Video

T Wowee RoboSapiens

Service Robots – Humanoids

- Hope is to replace humans in doing hard labor.
- No real sales yet.

Field Robots

- Do a useful task in structured or natural settings.
- Forceful interaction with the environment via implements.

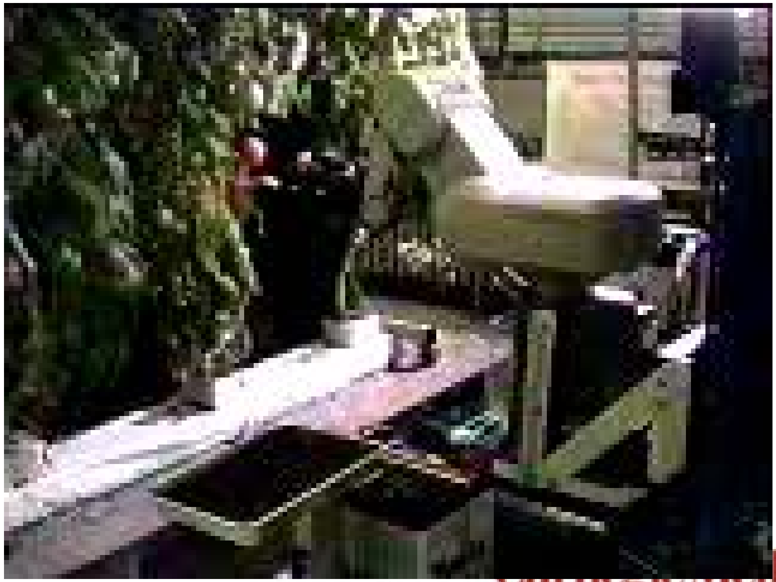
Deere Auto Fellerbuncher

Cat Auto Excavator

Excavation and Underground

Field Robots - Agriculture

- Applications include:
  - Planting
  - Weeding
  - Chemical application (herbicide, insecticide, fertilizer)
  - Pruning
  - Harvesting (picking fruit of all kinds)
  - Grading
- Large scale mowing on highways, golf courses.



Agriculture

Field Robots - Mi

- Open Pit:
  - Excavators, loaders, rock trucks, draglines.
- Underground:
  - Bolting machines
  - Continuous Mining machines
  - LHDs

Mining Trucks

Field Robots – U S A R

- Applications to disaster recovery
  - 9/11, Kobe Earthquake, Hurricane Katrina, Fukushima Nuclear Disaster.
  - Robots can:
    - Go where people cannot (physical / danger)
    - Sense what people cannot (heat)
    - Lift heavy objects…

Field Robots – U S A R

Tadokoro
USAR
Platform

Bombed
USAR

Field Robots – Recon & Surveillance

- Intended for military missions.
- US DOD recently awarded $180 Million to GDRS for military robot controllers.
- All weather, high mobility, stealthy, armored vehicles.
- “Weaponized” robots are close to deployment.

GDRS XUV

Recon and Surveillance

Field Robots – Recon & Surveillance

- iRobot has sold 300 packBots for use in Iraq.

iRobot packbot

Field Robots – Exploration

- MER Rovers Spirit and Opportunity went several kilometers autonomously in 2005.
- Teleop from Earth only twice a day.
- Automation Necessary.

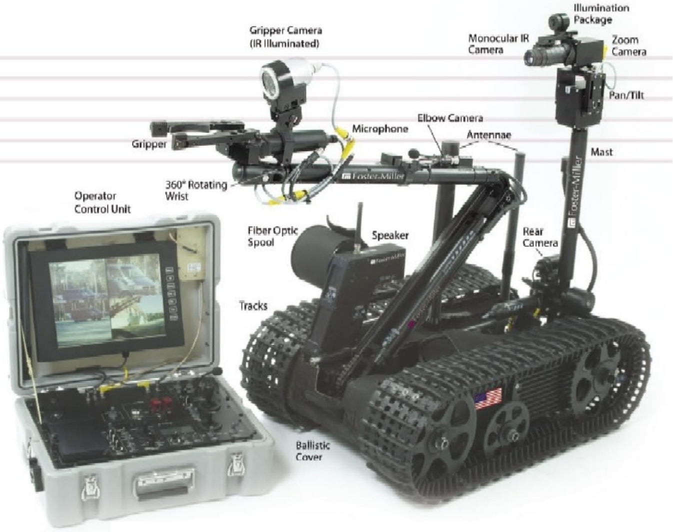
Mars Science Lab

Exploration

Field Robots – E

- Bomb disposal robot market is respectable.
- 2006: Foster Miller claims 50,000 missions completed to defuse devices in Iraq and Afganistan alone.
- $250 Million in Talon orders so far. $600 million in revenue.
- Apparently 6000 of these in Iraq in early 2006.

Northrop Grumman Andros Wolverine



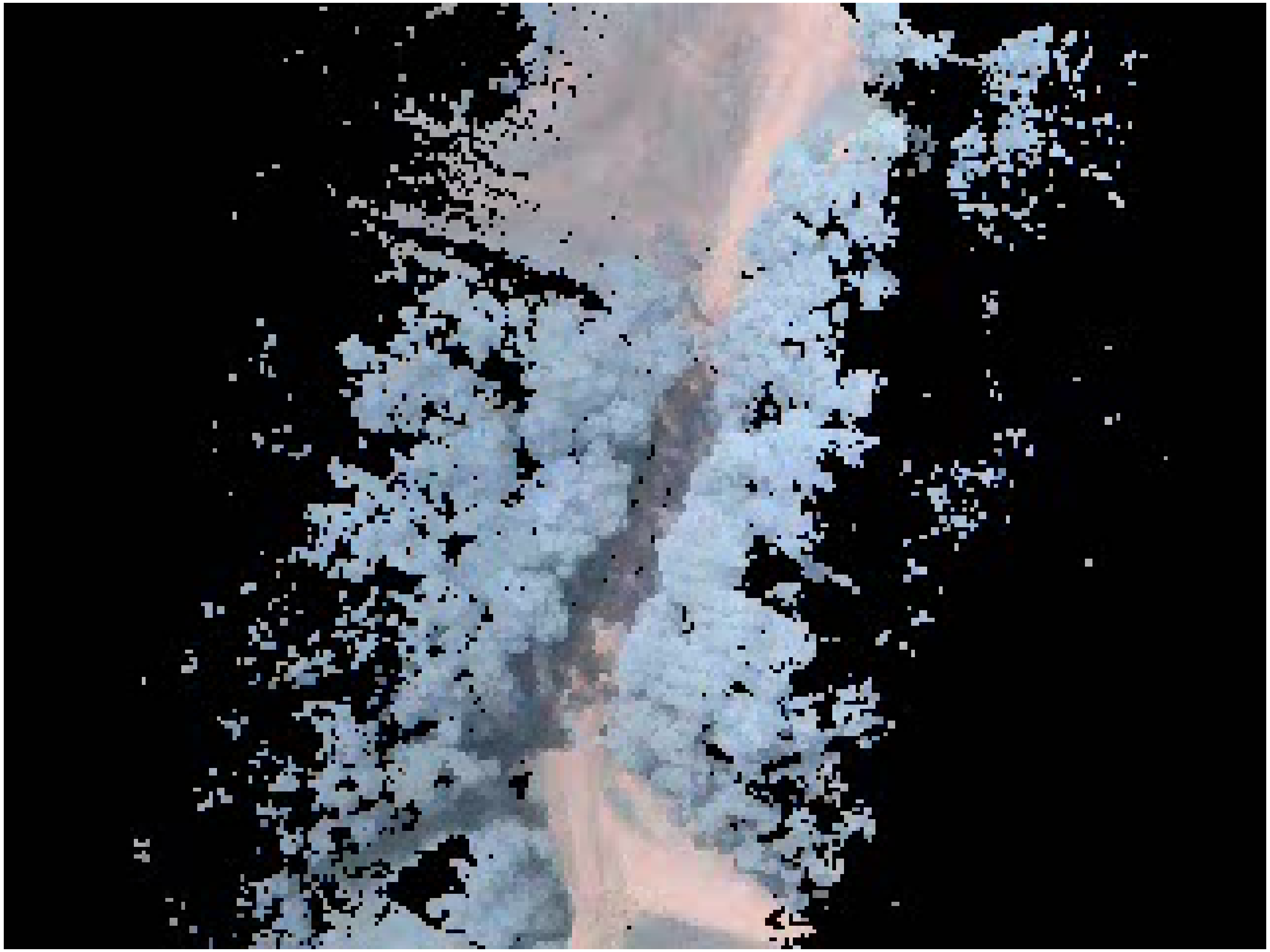
FosterMiller Talon

EOD

Field Robots - Mapping / Metrology

- Traffic Maps
- Forestry Inventory
- Mining Process Monitoring
- Military

Mapping / Metrology



Competition

- Robo Soccer
- Darpa Grand Challenge

Competition

Milestones - Commercial

- AGV sales at $300 Million in US in 2005.
- Australian port of Brisbane operating “lights out” 24/7 with dozens of robot straddle carriers.
- As of Jan 2006, iRobot has sold 1.2 million Roomba for $95 million in sales.
- 6000 Robots were in Iraq.

Milestones - Science

- Caterpillar automates mining truck in 1990.
- Automatic car crosses USA in 1995.
- MER Rovers drove kilometers autonomously on Mars in 2005.
- 4 robots completed the Grand Challenge in 2005.

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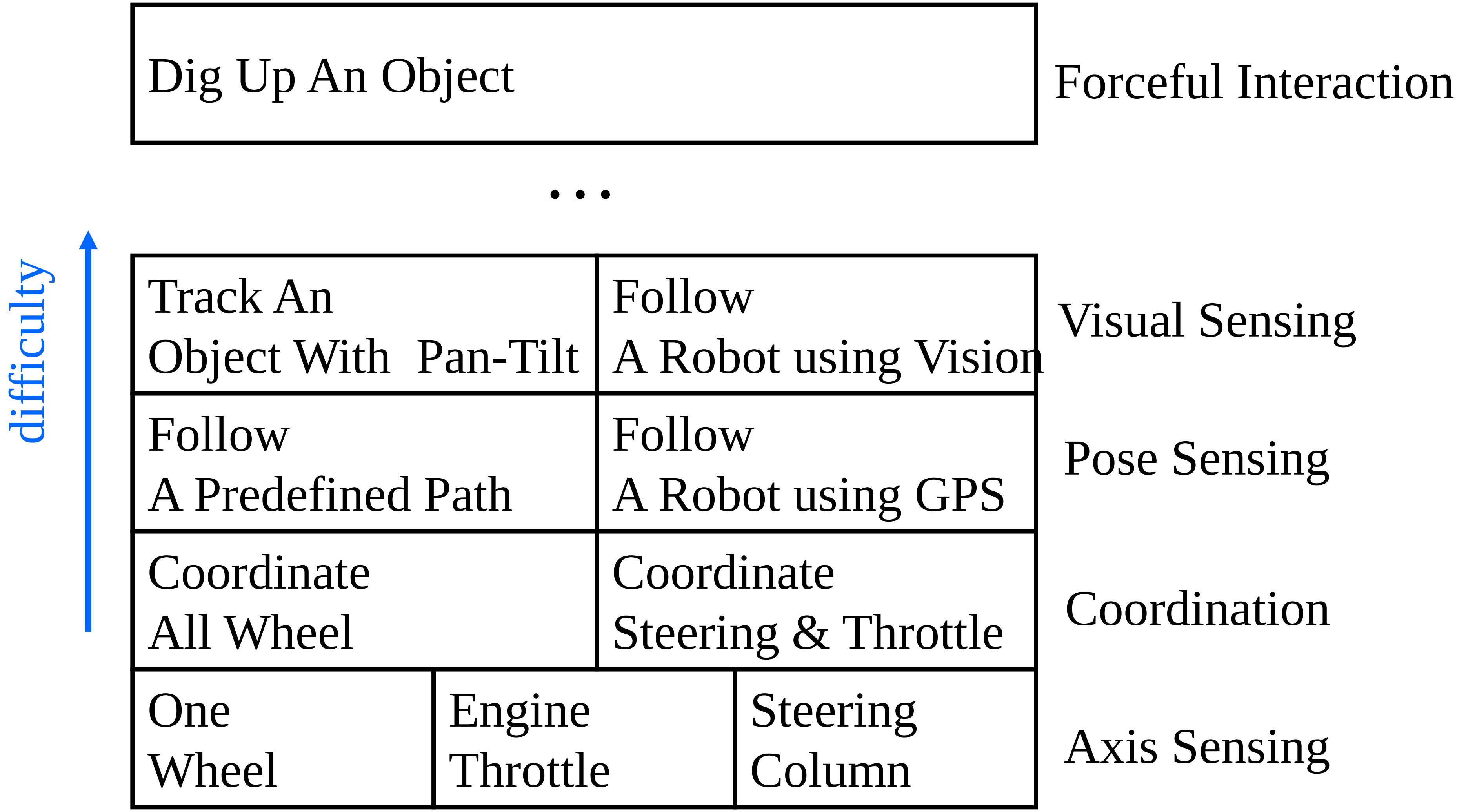
Subsystems - Control

- Just getting around requires Automatic Control:
  - Sense state of actuators such as steering, speed, wheel velocities.
  - Precision application of power to actuators to cause them to exert forces.
- To be autonomous, there needs to be a driver.
  - This course is mostly about building the driver for the robot.

Controls Objectives Spectrum



Dig Up An Object

Forceful Interaction

. . .

difficulty

Track An Object With Pan-Tilt

Follow A Robot using Vision

Visual Sensing

Follow A Predefined Path

Follow A Robot using GPS

Pose Sensing

Coordinate All Wheel

Coordinate Steering & Throttle

Coordination

One Wheel

Engine Throttle

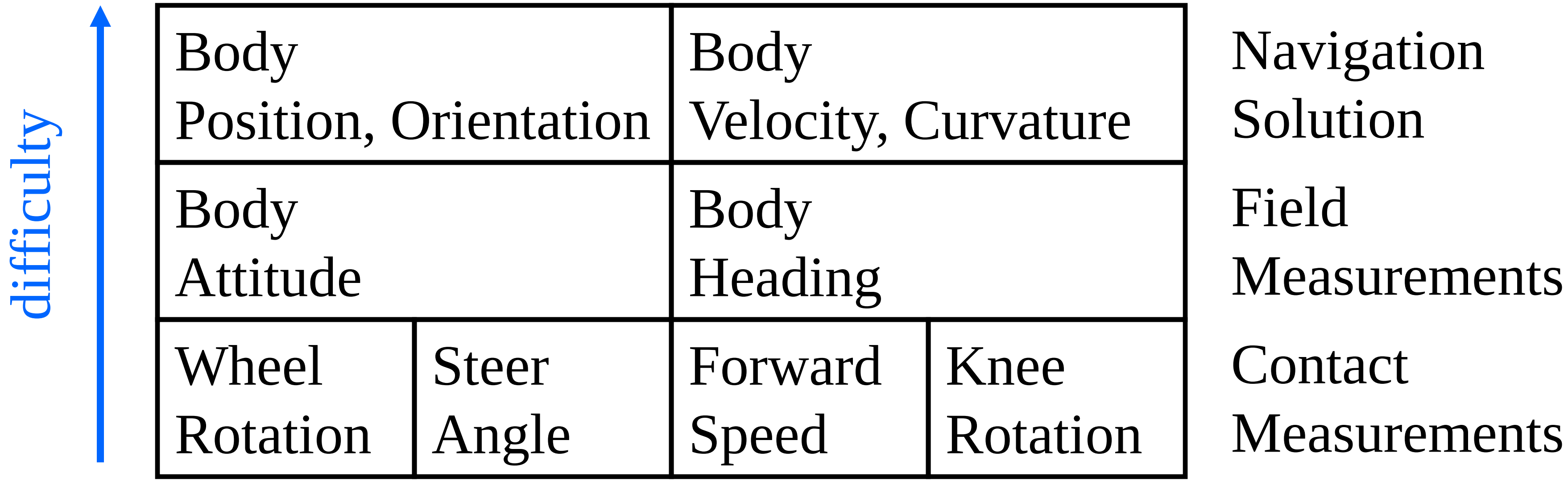
Steering Column

Axis Sensing

Subsystems - Navigation

- Getting somewhere in particular requires:
  - a means to know when you are there.
  - a means to know how to head toward it.
- State estimation combined with control lets you get from place to place.

Navigation Objectives Spectrum

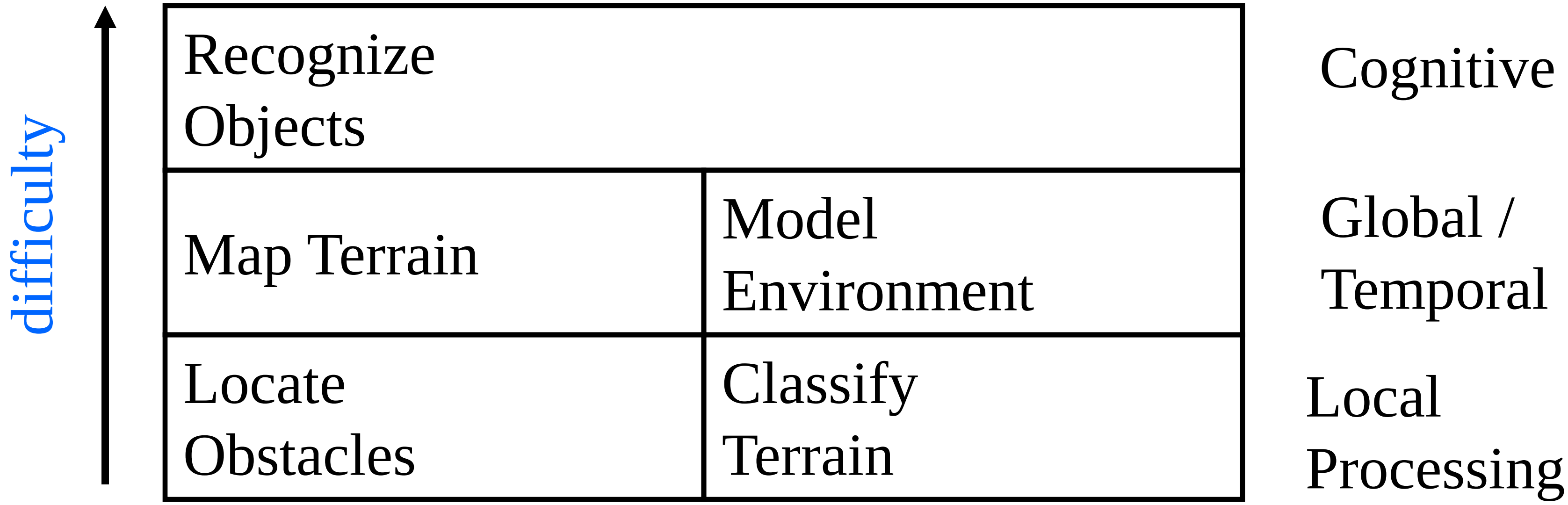


Body Position, Orientation		Body Velocity, Curvature		Navigation Solution
Body Attitude		Body Heading		Field Measurements
Wheel Rotation	Steer Angle	Forward Speed	Knee Rotation	Contact Measurements

Subsystems - Perception

- But this is blind moving.
  - What if there is something in the way?
  - -> Perception
- Perception enables intelligent responses to the immediate environment.
  - (Tracking) Follow the road
  - (Control) Dodge the fallen tree
  - (Cognition) Recognize the Mars lifeform

Perception Objectives Spectrum



Subsystems - Planning

- But you can’t perceive everything either. You need to:
  - Generate a plan of action, and update it.
  - -> Planning
- Planning implies a need to:
  - Remember what was seen by you or others (mapping)
  - Generate possible courses of action (search)
  - Predict the consequences of your actions (modeling).
  - Choose the one best suited to the situation (deliberation).
- And you need to do all this pretty quickly:
  - based on imperfect data
  - perhaps while moving pretty quickly

Planning Objectives Spectrum

difficulty

<table>
<tr><td colspan="2">Cover
An Area</td><td colspan="2">Replenish
Consumables</td><td colspan="2">Coordinate
Many Robots</td><td>Mission
Planning</td></tr>
<tr><td colspan="3">Plan Path
To a Goal (s)</td><td colspan="3">Replan Path(s)
Continuously</td><td>Path
Planning</td></tr>
<tr><td colspan="3">Stop For
Obstacle</td><td colspan="3">Drive Around
Obstacle</td><td>Reactive</td></tr>
</table>

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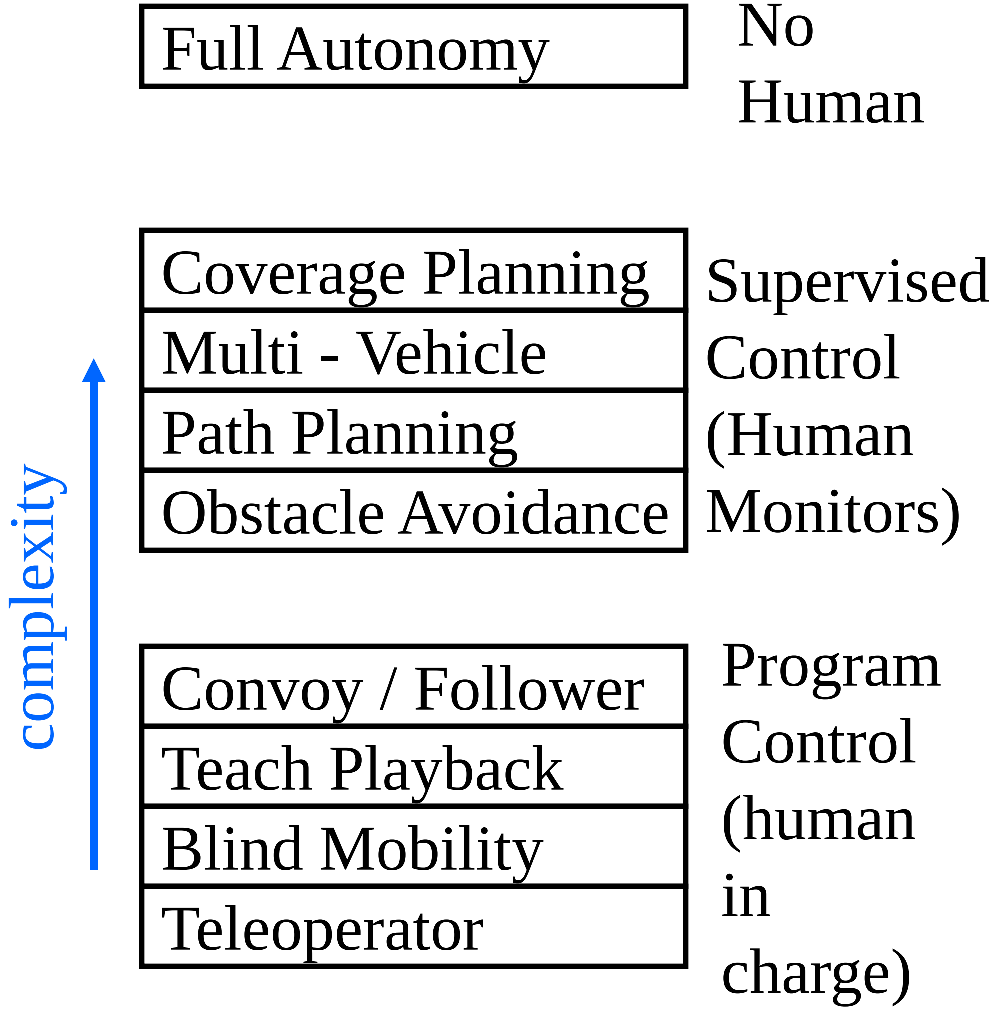
Levels of Autonomy / Complexity

	Simple	Complex
Cost	low	high
Make / Maintain	easy	hard
Operate	hard	easy
Tasks	easy	hard
robust	more	less



Full Autonomy

No Human

Coverage Planning
Multi - Vehicle
Path Planning
Obstacle Avoidance

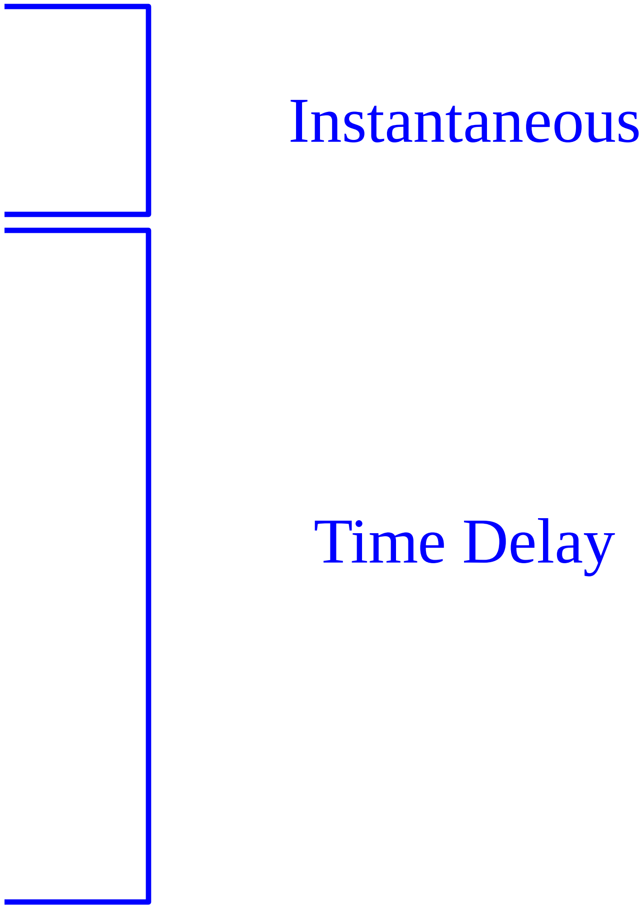
Supervised Control (Human Monitors)

Convoy / Follower
Teach Playback
Blind Mobility
Teleoperator

Program Control (human in charge)

Program Control (Human in Charge)

- Teleoperator - responds to user-supplied commands
- Blind mobility - executes a program of instructions
- Teach-playback - copies historical behavior of itself
- Convoy - copies behavior of another vehicle



Supervised Control and Autonomous

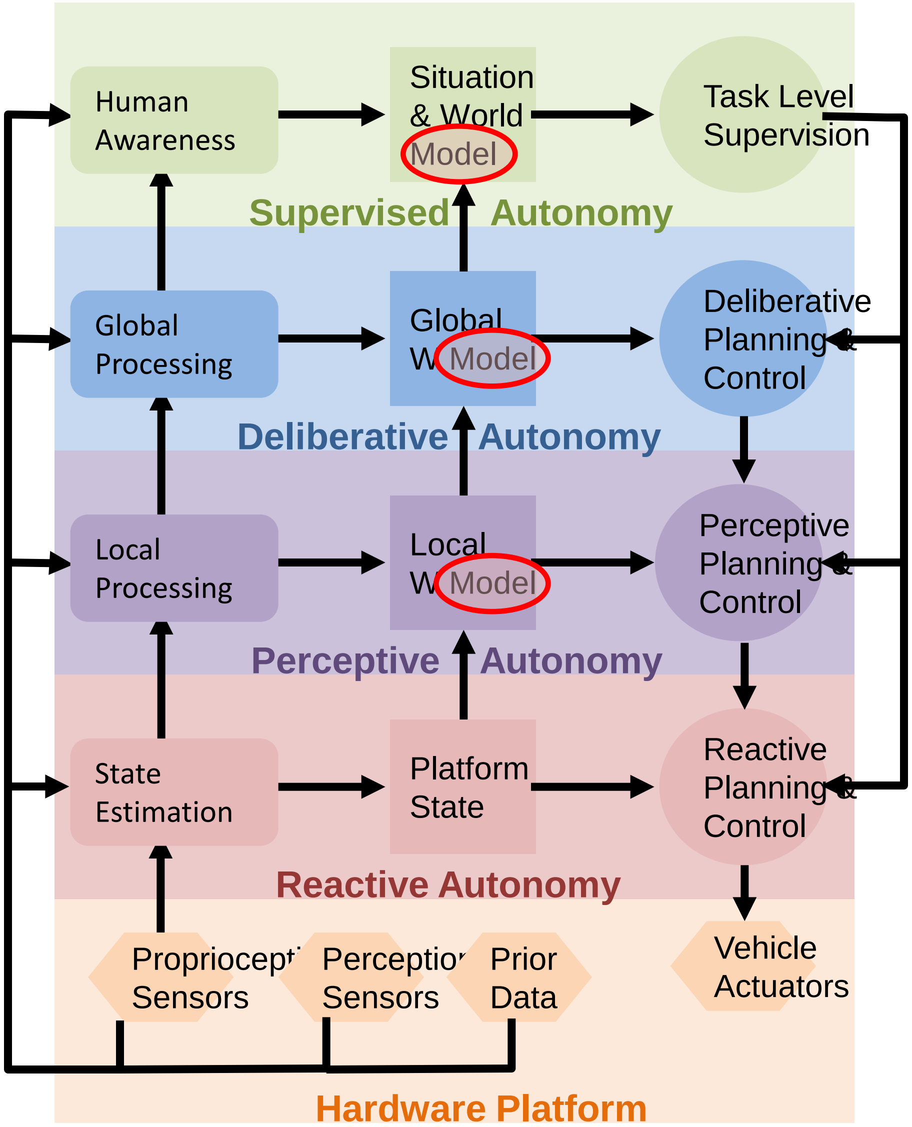
- Operator specifies <u>broad goals</u> at <u>various frequencies</u>
  - minutes, hours, days, weeks
- Full autonomy is but a dream today in <u>many</u> profitable applications.
  - But not all anymore

What is Autonomy?

- Three suggested aspects of how autonomous a system is:
  - “Level” of operator interaction.
    - Detail, frequency
  - Authority to make decisions.
    - Stop or avoid obstacles
  - Situational / Environmental Awareness
    - Authority to summarize for humans

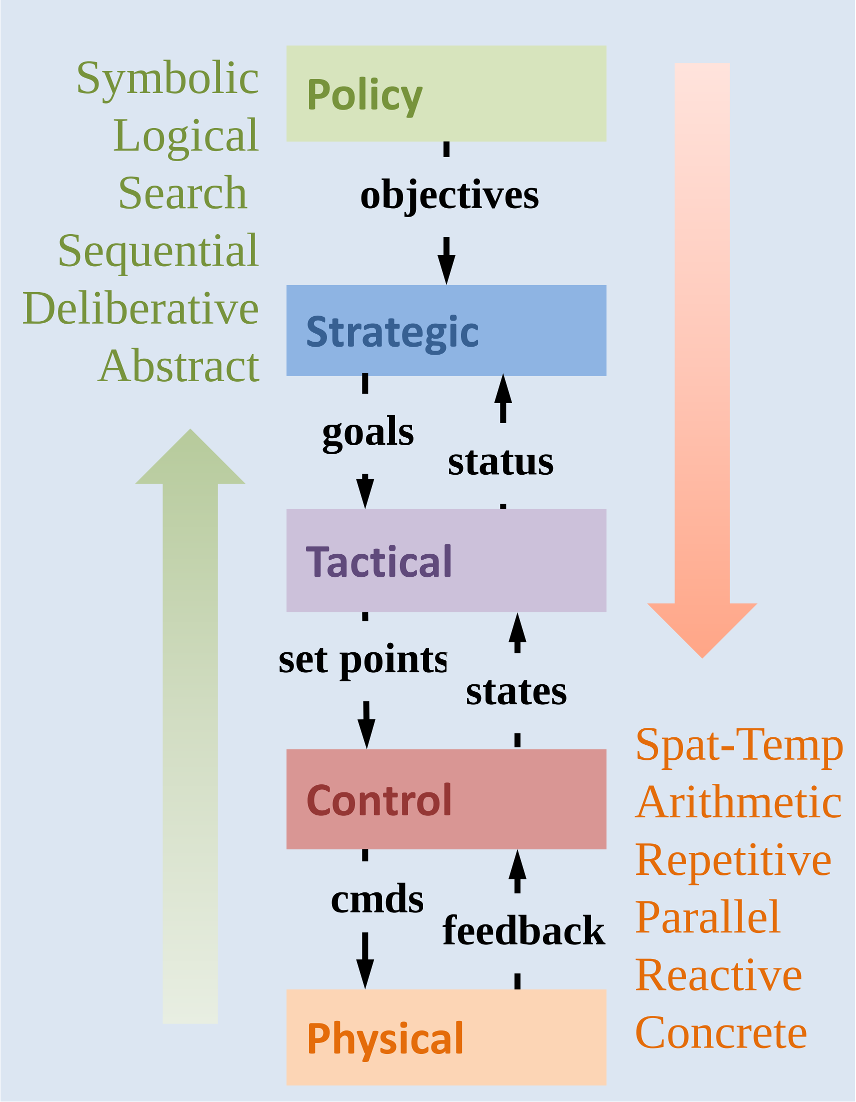
Autonomy in 5 Layers

- Nested control loops.
  - Commands, state, and models at all levels.
- Processing Levels
  - Supervise = …
  - Deliberate = decide
  - Perceive = see
  - React = …



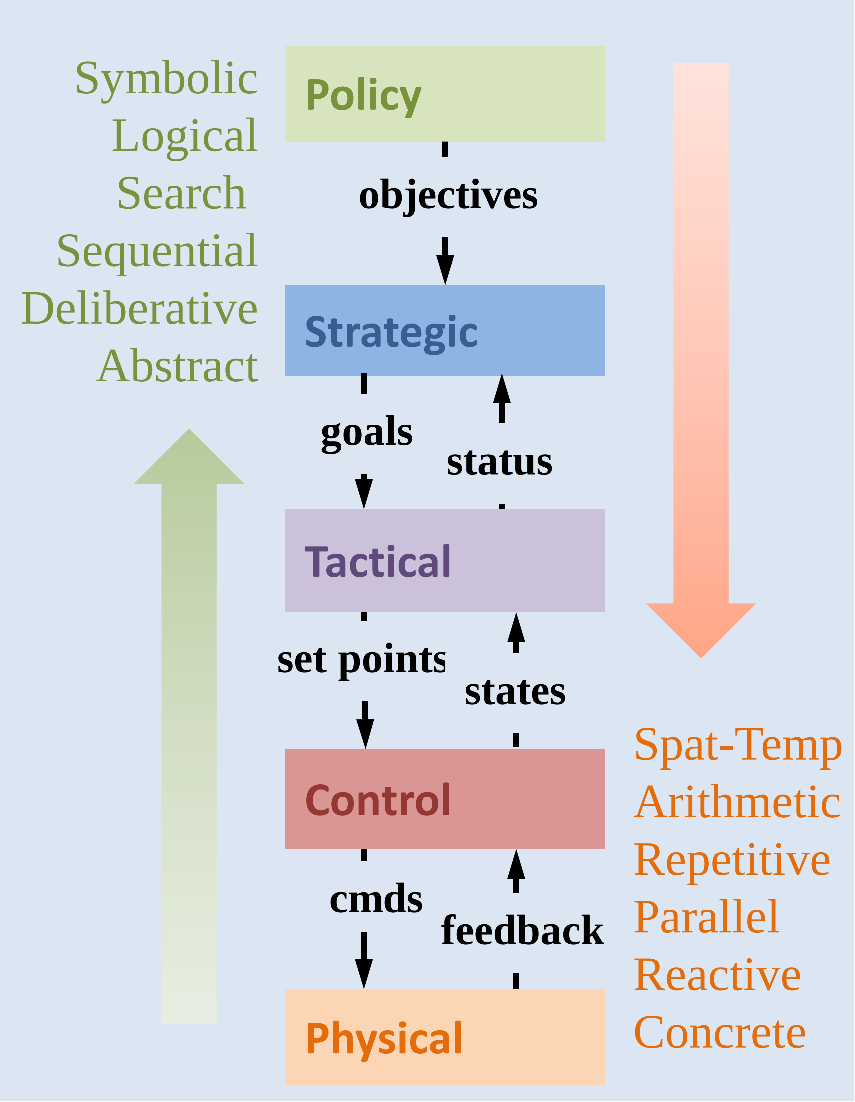
Computations

- Upper levels:
  - Symbols
  - Graphs
  - Propositions
  - Concepts
- Lower levels:
  - Signals
  - Fields
  - Vectors



Standard Architectural Model

- A simple hierarchy applies to most systems.
  - Contents of each box varies.
- Thinking takes time and higher levels think more, so they are slower.



Symbolic
Logical
Search
Sequential
Deliberative
Abstract

Policy

objectives

Strategic

goals

status

Tactical

set points

states

Control

cmds

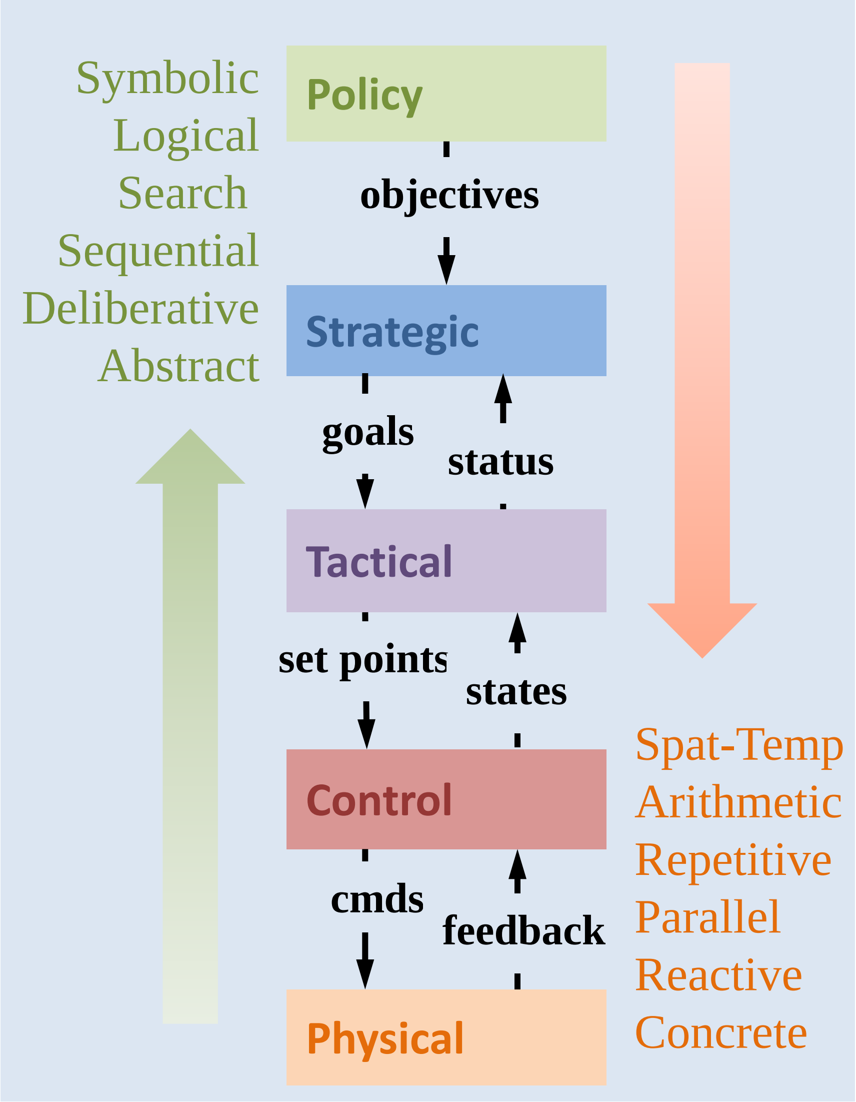
feedback

Physical

Spat-Temp
Arithmetic
Repetitive
Parallel
Reactive
Concrete

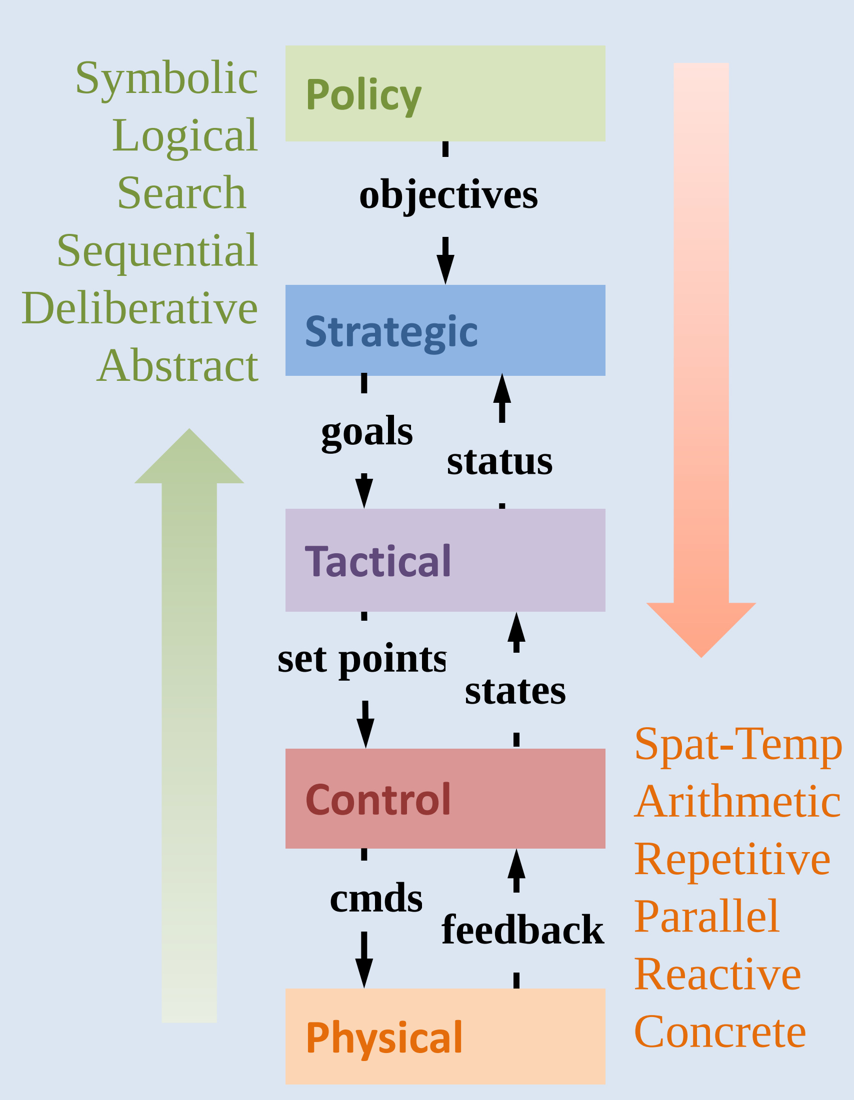
Policy Layer

- Generates the mission objectives like:
  - stay alive
  - find the X
- Usually, humans provide this and it is <u>hard coded</u>.



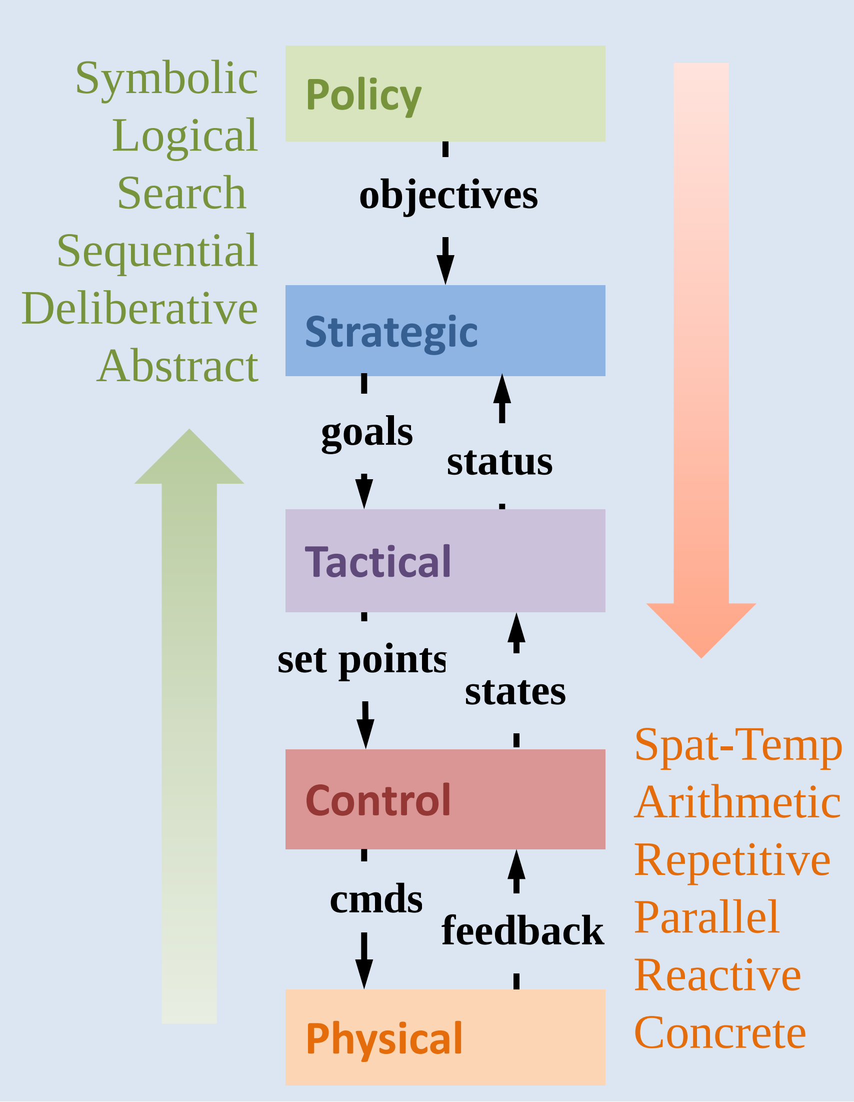
Strategic Layer

- The deliberative, logical, goal-generating component (deliberative intelligence)
- Responsible for enacting policy by
  - setting goals
  - avoiding getting trapped or lost by systematic search,
  - optimality
  - modeling and memory of the environment.
- AI and operations research techniques are used



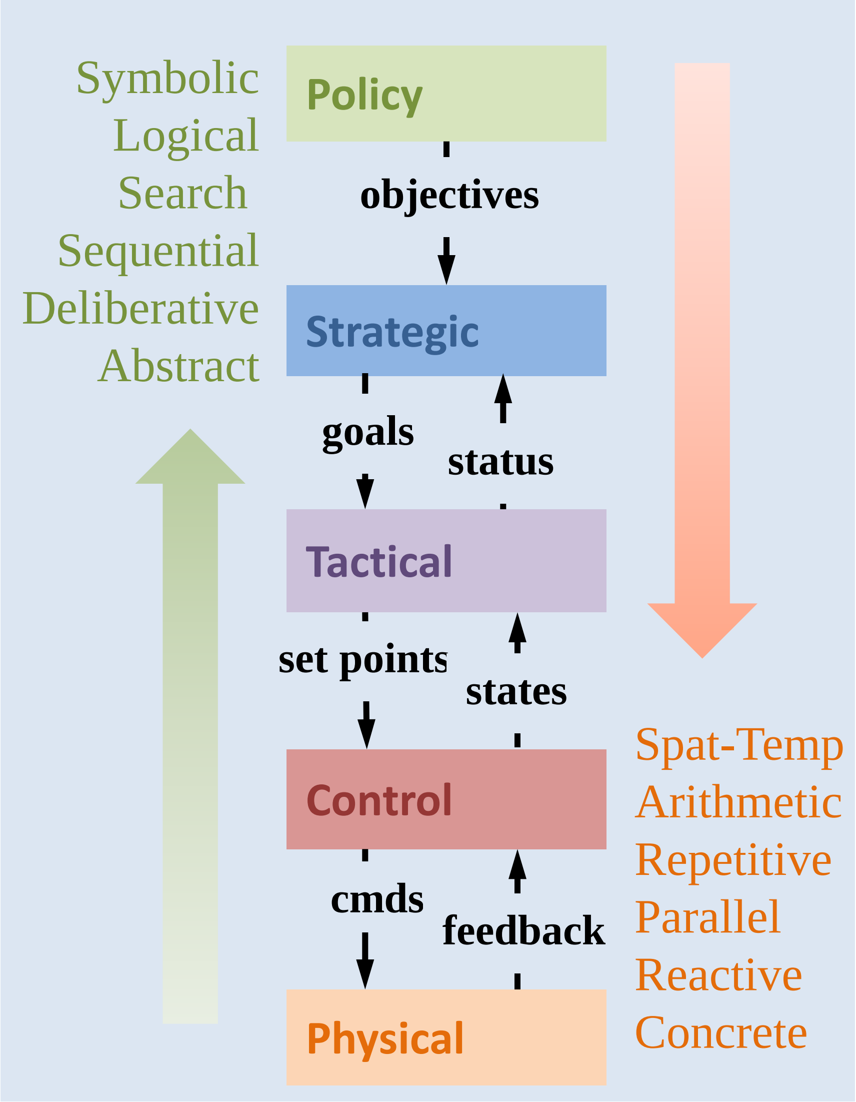
Tactical Layer

- Partly deliberative, partly reactive
- Responsible for:
  - immediate survival,
  - coordinated control,
  - immediate perceptual awareness of the environment (reactive intelligence)
- High level MIMO control techniques are used



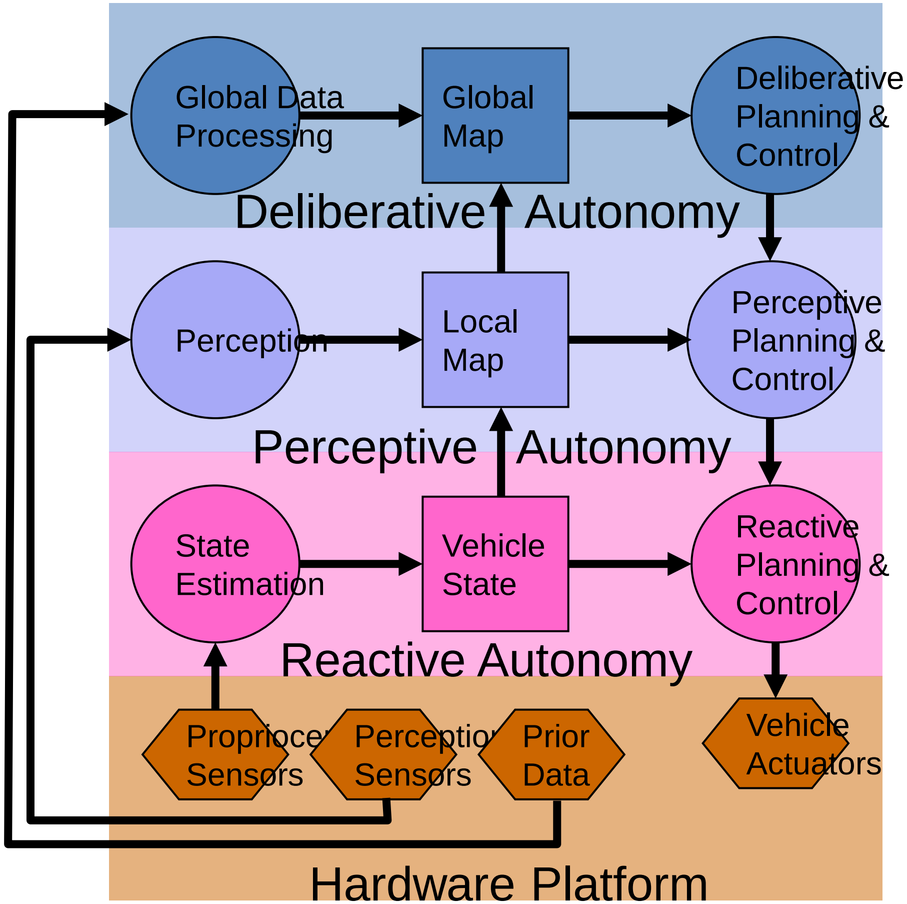
Control Layer

- Real-time command following component
- (Tries to) do exactly what it is told
- Normally models actuator and body dynamics
- Low level automatic control theory used



Nested Loop View of Architecture

- Three sense-plan-act loops.
  - Each has a “sensor”.
  - Each has a “planner”
  - Each has an “actuator”
- Capabilities working upward:
  - Drive blind
  - Drive reactively
  - Drive deliberately



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Physical Subsystems - Mechanical

- Chassis - provides physical structure for:
  - attaching everything else (e.g masts, booms)
  - bearing and distributing physical loads (e.g. trusses)
- Propulsion - provides the motive power of the system
  - electrical motors
  - chemical (IC) engines
- Suspension - distributes terrain following loads and maintains body posture
- Locomotion - translates raw motive power into actual motion of the vehicle body
  - legs and feet, wheels, tracks
  - exotics like serpentine, marine and space thrusters
- Auxiliary mechanisms
  - arms (not legs)
  - sensor heads (pan/tilt units)

Physical Subsystems - Power

- Auxiliary (in addition to propulsion) power units:
  - diesel and gas generators
  - solar arrays
- Power conditioning - cleans up, distributes, and/or stores energy:
  - uninterruptible power supplies
  - batteries and chargers
- Tethers - transmit any or all of:
  - power
  - force
  - telemetry (data communications)

Physical Subsystems - Sensing

- Proprioceptive sensors - measure the internal motions of mechanisms
  - encoders, resolvers, tachometers
  - potentiometers, LVDTs
- Position estimation sensors - measure things related to where the vehicle is:
  - compasses, gyros, odometry,
  - accelerometers, inclinometers, INS
  - GPS
- Perception sensors - measure things related to the environment external to the vehicle.
  - whiskers, bumpers, limit switches
  - force and torque transducers
  - sonar and infrared beams
  - imaging ladar, radar, sonar, stereo, cameras
  - capacitive, inductive, magnetic etc. proxes
  - exotics
- Antennae
  - navigation radio signals
  - telemetry (e.g. cellular modem)
  - magnetic flux

Physical Subsystems – Control

- Motion control:
  - steering - controls the direction of
  - speed - controls the magnitude of
  - may be coupled or decoupled

- Environmental control - make things comfy for people and/or electronics
  - air conditioning
  - forced air or solid state cooling
  - radiators and heat pipes

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Design Issues – Planning

- Deliberative versus reactive
  - how much look ahead is necessary
  - how much memory is necessary
- Managing combinatoric explosion
- Errors. What is an exception, what should be planned for
- Lookahead / cycle time tradeoff
- Completeness, optimality
- Goal arbitration and conflict resolution
  - goal seeking
  - obstacle avoidance
- Uncertainty

Design Issues – Modeling

- What is the best representation for a given task
  - images, maps, vectors, symbols
  - navigable, traversible, or free space
  - Configuration/work space
  - operators / states
- What sort of vehicle model is necessary?
- Fusion
  - how should redundant measurements be fused
  - how should redundant sensor modalities be fused
- How to track dynamic environments well enough

Design Issues – Sensing

- Will we ever have / how to do without
  - decent sensors
  - fast enough computers
- Hi res is too much data to compute
- Lo res is too little to be useful

Design Issues – Awareness

- Some problems seem to require common sense reasoning - uh oh!.
  - Avoiding risk when you have the luxury.
  - Being aggressive when the situation demands.
  - Knowing the coming narrow passage is critical to get through.

Outline

- Taxonomy
- Applications and Markets
- Subsystems
- Architecture
- Mechanical Configuration
- Design Themes & Issues
- Summary

Mobile Robots

- Their time has finally come …
  - They continue to invade our culture.
  - Established markets exist.
- They go where no man has gone before.
  - Agents for science, exploration, human care, industry.
- There is lots to know about them.
- ….Universities should teach courses on this stuff…