Introduction to Mobile Robots
1 Definitions & Distinctions

• Robotics:
  • “The Intelligent Connection of Perception to Action”, (Mike Brady, 1985)

• Robot:
  • Japan: “Any device which replaces human labour”, (Sosoka, 1985)
  • RIA: A programmable multi-function manipulator designed to move material, parts, or specialized devices through variable programmed motions for the performance of a variety of tasks”, (Schlussel, 1985)

• Mobile Robot:
  • Any robot which possesses mobility with respect to a medium?
  • Any system which is:
    • mobile - entire system moves wrt environment
    • somewhat autonomous - limited human interaction
    • intelligent - senses and reacts to its environment

For our purposes the terms mobile robot, vehicle, robot, and system will normally be synonyms.
2 Taxonomy of Mobile Robots

May classify mobile robots on several independent axes, each of which affects key aspects of their control software.

2.1 Terrainability (Ability to negotiate terrain)
- Indoor or Outdoor
- affects complexity of world model and alot more

2.2 Type of Locomotion
- Wheeled, Legged, Tracked, Serpentine
- affects path mobility models in planning

2.3 Type of Steering
- Ackerman, Synchronous, Skid, etc.
- affects mobility models in planning

2.4 Body Flexibility
- Unibody or Multi body, Flexible or Rigid body
- affects complexity of perception data processing

2.5 Shape
- Simple or complex, Soup Can vs Insect-Like
- dramatically affects complexity of obstacle avoidance during planning

2.6 General Class
- AGVs, Service Robots, Research, Education
- affects user interfaces, quality, packaging
2.7 Lineage

- Retrofitted or Custom vehicle
- affects development cost versus ease

2.8 Medium of Transport

- Land, Water, Fuel, Pipes, Air, Undersea, Space
- affects mechanism for coordinate actuator control

2.9 Level of Autonomy

- Teleoperator to Fully Autonomous
- affects complexity of all levels of control software
3 Goals & Purposes

3.1 Access (Do it)
- Provide access where there was none before because of:
  - hazard
  - environment (no air, too high pressure, etc.)
  - distance/time (Mars etc.)

3.2 Reduced Cost (Cheaper)
- reduced operating costs due to lower cost of employing robots
  - lower overheads
- reduced maintenance costs due to uniform and gentle treatment of capital equipment and the vehicle itself

3.3 Increased Productivity (Faster)
- higher overall availability of robot workers (no lunch breaks or vacations).
- higher material throughput or other working rate of robots versus humans (paint, cut, move faster).
- reduced use of precious resources such as floor space and order filling time reduces overhead costs.

3.4 Improved Product Quality (Better)
- Improved product/service quality
4 Potential Applications

Mobile robots have potential applications everywhere that a vehicle or a large conveyor or manipulator could be used, or already is used today.

Everywhere there is a vehicle today, someone drives that vehicle, but it could be a robot.

Everywhere there is a domesticated animal today doing work (pet dog, farm horse, oxen) there could be a robot.

4.1 Medical Service

- deliver food, water, newspapers, linens etc.
- “go fur” lab samples and specimens, medication, medical records, special meals, administrative reports, hazardous material, biological waste.
- pharmacy automation - dispensing medications

4.2 Commercial Cleaning

- airports, supermarkets, malls, factories, etc.
- lots of floor treatments like wash, sweep, mop, scrub, buff, wax, polish, vacuum, strip, shampoo, trash pick-up
- other unpleasant jobs like washing bathrooms, windows, upholstery

4.3 Consumer Sales

- supermarket go-fur
- restaurant gimicky order-taking and delivery
- automated gas pump
4.4 Agriculture

- in 1870, it took 47% of US workforce to feed itself but today, less than 3% of our workforce generates food
- planting, weeding, chemical applications, pruning, mowing, harvesting and picking fruit and vegetables.

4.5 Forestry

- tending trees (herbicides, insecticides, fertilizers)
- pruning of Xmas trees
- harvesting pulp and hardwood (automated fellerbuncher)

4.6 Lawn Care

- consumer lawn care (on the market now)
- golf courses
- highway median mowing

4.7 Hazardous & Energy

- bomb and mine mapping, retrieval and disposal
- nuclear plant inspection, steam generators and calandria
- hazardous waste storage tank inspection
- pipeline inspection crawlers
- high tension powerline inspection

4.8 Mining / Excavation

- earth moving excavators, loaders, dozers
- strip mine rock trucks and underground LHD’s
- automated rock breaking manipulators
4.9 Construction / Demolition

• automated cranes
• delivery and levelling of concrete

4.10 Space

• terrestrial inspections of space vehicles
• satellite on-orbit inspection
• planetary exploration

4.11 Undersea

• drilling platform inspection
• transatlantic cable installation and maintenance
• exploration (found the Titanic this way)

4.12 Military

• reconnaissance vehicles
• troop resupply
• automated ambulance

4.13 Shipping / Warehousing / Material Handling

• AGVs operate successfully today in highly structured automotive and electronics factories.
• loading and unloading of trucks, trains, ships, and planes.

4.14 Security

• surveillance of large warehouses, buildings, parking garages after hours
4.15 Civil Transport

- aircraft inspection
- automated and/or intelligent highway vehicles

4.16 Personal

- assistants for handicapped and elderly individuals
- assist with personal hygiene, working at home, recreation
- seeing eye robot, smart self-navigating wheelchair

4.17 Entertainment

- RoboDog
- Rover Telepresence
5 Examples of Mobile Robots

5.1 Class: Automated Guided Vehicles (AGVs)

- Class includes tuggers (tugs), carriers (unit load) and fork-type vehicles.
- Purpose is industrial material handling in factories and indoor/outdoor shipping areas/warehouses.
- Invented in 1950s. First installed in 1954 by the Cravens Company at Mercury Motor Express in Columbia, SC.
- Industry peak was $175M in U.S. sales in 1985. Still recovering. Demag estimates <$400 M worldwide today.
- Originally and generally based on embedded wire guidance which requires expensive changes to plant infrastructure to install the wires.
- Newer ones from FMC (Food Machinery Corp.) based on rotating laser scanner and bar code retroreflectors - originally developed by Caterpillar.
- Demag now sells VirtualPath™ which is basically inertial guidance.
- Other current manufacturers are AGV Products, BT Systems, FROG Navigation, dozens more.
5.1.1 Rapistan-Demag AGVs

Features include:

• real-time communications
• on board routing and traffic logic
• auto return for charging
• inertial / odometric (non-wire) guidance
5.2 Class: Service Robots

- Players are/were Denning (now Pittsburgh, PA), Cybermotion/Cybermation (Roanoke, VA), TRC/Helpmate (Danbury, CT).
- Class includes vehicles for light material handling (mail, food), surveillance, floor cleaning.
- Cleaning robots in use in French subways.
- International Service Robots Association (ISRA) in Ann Arbor MI.

5.2.1 TRC Helpmate (TRC is now called HelpMate Robotics)

- Features include:
  - elevator interfaces
  - door openers
- Sold as a “trackless robotic courier”
- For transport of medical records, food, drugs.
- 90 Units sold by April 1996
- Can be rented for $6 / hour (“very cost-effective”?)
- Estimated U.S. market of 10,000 units
5.2.2 Windsor Industries PowerTec 26

- “Automated Hard Floor Cleaning System”
- cleans 100,000 square feet on a single charge
- laser/retroreflector plus odometry positioning
- two front scrubbers followed by rear squeegee

(Related Product Image)

- up to 2.5 m/sec speed
- 21 gallon cleaning solution tank
- 6, 6 volt, 305 amp-hr batteries
- 26” cleaning width
5.3 Class: Research Platforms

• Players are Denning (Pittsburgh, PA), RWI (Real World Interface, NH), Cybermation/Cybermotion, Nomadic Technologies. Dozens of others.

• Many commercial service robot vendors sell a research version of their products.

5.3.1 Real World Interface Model B21

• Modular design includes these modules:
  • robot base
  • control and sensory enclosure
  • external charging station
  • four axis arm

• Features include:
  • 4 wheel synchronous drive
  • 32 inches per second top speed
  • 100 lbs payload

• Sold as an open architecture platform for R&D

• Linux operating system and bundled RWI-C robot control libraries
5.3.2 Nomadic Technologies, Nomad 200

- targeted toward teaching and research
- hardware system provides
  - sensor and motor control
  - host computer communication
- software provides
  - graphic interface
  - robot simulator
  - motion planning and control libraries
  - sensor interpretation libraries
- you provide the hard part

- 3 wheel synchronous drive system with zero turn radius
- independent upper stage (turret) rotation
- 20 inch/sec, 60 degree/sec max speed
- 432 watt-hour battery
5.4 Class: Planetary Rovers

5.4.1 Dante II Rover Prototype

• frame walker
• 8 Pantograph Legs
• Went to Antartica, then Alaska
• first rapelling robot?
• fiber optic link to base stn, then to 1 Kbps satellite link.
• color stereo pair, laser rangefinder, color zoom and leg mounted cameras.
• H₂S, SO₂, CO₂ gas sensors.
• VME cages housing MC68000 and SPARC computing.

• 1700 lbs supported by 100 ft long 0.45 inch tether.
• 2 KW nominal power consumption
5.4.2 MESUR Pathfinder Micro Rover

- Developed by JPL mobile robots group
- Uses novel single line laser scanner (light striper) and stereo vision.
- Rocker-bogie suspension for high terrainability and stable instrument attitude control.
- Retractable body for minimum flight volume.
- Cleated steel foil wheels for high ground traction with low weight.
- New issue of lander and rover perceptual fusion.
5.5 Others of Note

There are well over 100 mobile robot designs that have been constructed plus a few others that were never built but are valuable concepts.

- Ghengis Microrover (MIT subsumption insect)
- JPL Robby (JPL Rover prototype, segmented body)
- Odetics Odex - commercial spider-like vehicle
- NAVLAB series (CMU retrofitted military and passenger vehicles)
- Uranus (CMU Illeanator wheels)
- Shakey/Stanford Cart (Cal Tech - first mobile robot in history)
- AMBLER (CMU legged Mars rover prototype)
- HILARE (Early French robot)
- ASV - Adaptive Suspension Vehicle (OSU teleoperated hydraulic legged vehicle)
- ALV - Autonomous Land Vehicle (Hughes/CMU first outdoor wheeled robot)
- Cybermotion Navmaster - commercial indoor research vehicle
- Denning Sentry - commercial service robot
- OMV - (NASA Orbital Maneuvering Vehicle)
- RANGER - (free-flying prototype)
6 Major Physical Subsystems

6.1 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)

6.2 Electrical Power and Signal

- auxiliary power unit(s) - generate power in addition to that generated by the propulsion system, typically for the purposes of supplying the additional automation hardware with power:
  - 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)

**6.3 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, odometry, gyros, 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
  • magnetic flux
• navigation radio signals
• telemetry (e.g. cellular modem)

6.4 Infrastructure

• beacons and repeaters
• bar codes, retroreflectors, passive transponders
• embedded paths based on buried wires, colored stripes, ultraviolet paints
• artificial optical fields like floor grids and patterns

6.5 Control

• motion control:
  • steering - controls the direction of \( \vec{V} \)
  • speed - controls the magnitude of \( \vec{V} \)
  • 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
7 Mobile Robots are Mobile

Mobile robots are fundamentally different from manipulators. Issues of mobility are so deep that an entire new subfield of robotics (mobile robotics) has sprung up to solve them:

Table 1: Mobile Robotic Problems and Solutions

<table>
<thead>
<tr>
<th>Mobile Robots Need To:</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>know where they are</td>
<td>navigation (position estimation)</td>
</tr>
<tr>
<td>know what’s out there</td>
<td>perception</td>
</tr>
<tr>
<td>model both of these in order to think about them</td>
<td>representation</td>
</tr>
<tr>
<td>using the representation of the current situation, and the mission goals, decide what to do next</td>
<td>planning</td>
</tr>
<tr>
<td>decide this even when the representation is imperfect, and when commands are not executed perfectly</td>
<td>uncertainty</td>
</tr>
<tr>
<td>be able to execute and monitor compliance with this plan</td>
<td>control</td>
</tr>
<tr>
<td>be embodied in real hardware</td>
<td>mechanisms</td>
</tr>
</tbody>
</table>

- this is the classical PERCEIVE - THINK - ACT cycle of robotic control
8 Levels of Autonomy

- A spectrum of capabilities exists.
- Simpler systems are cheaper, easier to make and maintain, perhaps harder to operate, and more robust at the simple tasks they perform.
- More complex systems are expensive, hard to make and maintain, perhaps easier to operate, and less robust at the complex tasks that they perform.

<table>
<thead>
<tr>
<th>Simple</th>
<th>Complex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teleoperator</td>
<td>Totally Autonomous</td>
</tr>
<tr>
<td>Blind Mobility</td>
<td></td>
</tr>
<tr>
<td>Teach/Playback</td>
<td></td>
</tr>
<tr>
<td>Convoy Follower</td>
<td></td>
</tr>
<tr>
<td>Program Control</td>
<td>Supervised Control</td>
</tr>
<tr>
<td>Human Operator</td>
<td>Autonomous</td>
</tr>
<tr>
<td>Is In Charge</td>
<td>Human Operator</td>
</tr>
<tr>
<td></td>
<td>Is Monitoring</td>
</tr>
</tbody>
</table>

- Program Control Levels
  - teleoperator - responds to user-supplied commands
  - convoy - copies behavior of another vehicle
  - teach-playback - copies historical behavior of itself
• blind mobility - executes a program of instructions
• Supervised Control and Autonomous Levels
  • operator specifies broad goals at various frequencies
  • minutes, hours, days, weeks
  • fully autonomous is but a dream today
• Issues include “does the autonomous system”:
  • Ensure its own survival
  • Define policy (probably not)
  • Set its own goals (maybe)
  • Juggle simultaneous, yet, conflicting goals
  • Plan its own actions to achieve those goals
  • Deal with its own problems (exceptions)
  • Report its own status (without a human interpreter)
  • Direct the actions of others
9 Standard Architectural Model?

A hierarchy, though not too sophisticated, seems to explain the high-level architecture of most systems, though what goes on inside each box may vary.

- Higher layers tend to have longer reaction and cycle times.
- Higher levels tend to consider more alternatives before a decision is made. Hence, they tend to be more empowered to deal with exceptions by utilizing other options.
9.1 Policy Layer

- generates the mission objectives like:
  - stay alive
  - find the X
- usually, humans provide this

9.2 Strategic Layer

- the deliberative, logical, goal-generating component
- responsible for enacting policy by setting goals, avoiding getting trapped or lost, optimality, modelling and memory of the environment.
- AI and operations research techniques used.

9.3 Control Layer

- real-time command following component
- does exactly what it is told
- automatic control theory used

9.4 Tactical Layer

- partly deliberative, partly reactive
- responsible for immediate survival, coordinated control, immediate perceptual awareness of the environment
10 Capabilities and Behaviors

The course will roughly follow a sequence of steps necessary to construct a working mobile robot. Some milestones along the way might be:

10.1 Position Estimation

- able to measure rotation of the wheels
- able to compute speed and heading
- able to measure position of the leg joints
- able to compute position and attitude
- able to measure speed and heading
- able to compute \(x, y, w\) in the plane
- able to measure attitude rate and linear acceleration
- able to compute \(x, y, z, r, p, w\) in 3D

10.2 Control

- able to control one wheel rotation
- able to coordinate all wheels
- able to control engine speed
- able to control steering column
- able to coordinate steering and speed
- able to follow a predefined path, another robot
- able to look at an object on demand
- able to track an object
- able to dig up an object
10.3 Perception

- able to locate obstacles (obstacle detection)
- able to classify terrain
- able to map terrain (map building)
- able to identify objects (object recognition)
- able to represent the whole environment (modelling)

10.4 Planning

- able to stop for an obstacle
- able to drive around an obstacle (obstacle avoidance)
- able to plan a trajectory to a goal (trajectory planning)
- able to plan a sequence of trajectories (route planning)
- able to replan in the face of new information
- able to cover an area
- able to replenish consumables
- able to coordinate several vehicles
11 Some Big Questions and Issues

• Planning
  • deliberative versus reactive
    • how much lookahead is necessary
    • how much memory is necessary
  • managing combinatoric explosion
  • what is an exception, what should be planned for
  • lookahead / cycle time tradeoff
  • completeness, optimality
  • goal arbitration and conflict resolution
    • goal seeking
    • obstacle avoidance
  • scheduling tasks
    • synchronous (obstacle avoidance)
    • asynchronous (landmark recognition)

• Modelling
  • what is the best representation for a given task
    • images, maps, vectors, symbols
    • navigable, traversible, or free space
    • configuration space or operators and states
  • fusion
    • how should redundant measurements be fused
    • how should redundant sensor modalities be fused
  • what sort of vehicle model is necessary?
• how to track dynamic environments well enough
  • Uncertainty
    • uncertainty versus models
      • how much error is model error, how much noise
    • when are linear Kalman assumptions valid
    • decoupling motion and perceptive errors
  • 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
  • Architecture
    • distributed planning and representation

**12 References**

Engleberger, *Robotics in Service*

Various, *Fundamentals of Robot Technology*

Elfes, *Autonomous Mobile Robots*. 
13 Notes

- Other robots worth mentioning include:
  - RATLER, other SANDIA vehicles
  - Lunakhod
  - RSI indoor and outdoor
  - Flying / undersea
  - ABE - Autonomous Bendig Explorer?
  - Demeter
  - Robart II and II (Everett)