From Personal Computers to Personal Robots

Challenges in Computer Science Education

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Mechanism vs. Computer

Unimate (1961)  
IBM 704 (1964)
From Personal Computers to Personal Robots

Computers + Sensors & Actuators -> **Personal Robots** <- Computers & Sensors + Actuators
Driver #2: Sensors
State of the Art

Mobility (1st semester)

KIVA Systems

Rethink Robotics

Manipulation (2nd semester)

Orbotix

"Let me drive this around for a second." - President Barack Obama

Modular Robotics
Technical Challenges

• Uncertainty (sensing/actuation) requires shift from **deterministic** to **probabilistic** reasoning

• Robots are systems-of-systems consisting of hundreds of heterogeneous, distributed computing elements

• Computing interactions with the world requires **understanding of the physical world’s dynamics**

• Play and backlash in mechanism
• 7 micro-controllers + 1 PC
• Non-trivial mass to accelerate

=> Need “Robotics” classes within CS curriculum
Technical Challenges

- Uncertainty (sensing/actuation) requires shift from deterministic to probabilistic reasoning.
- Robots are systems of systems consisting of hundreds of heterogeneous, distributed computing elements.
- Computing interactions with the world requires understanding of the physical world's dynamics.
- Play and backlash in mechanism:
  - 7 micro-controllers + 1 PC
  - Non-trivial mass to accelerate

Artificial Intelligence

Cyber-Physical Systems

Software Engineering

Programming Languages

Robotics

Natural Language Processing

Computer Vision

Computer Graphics

=> Need “Robotics” classes within CS curriculum
Educational Challenges

• Scalability

• Assessment

• Complexity
Approach

• Tight integration of simulation and real world experimentation
• Systematic experimentation and portfolio-based assessment
• Goal-based learning inspired by industry drivers
1\textsuperscript{st} Semester: Robotic Maze Competition

• Find “chargers” in the environment before you run out of power

• Tactics
  – Random Walk
  – Wall following
  – Simultaneous Localization and Mapping

• Simulator can control real robots via Bluetooth based on real-time sensor data
Locomotion and Manipulation

• Coordinate frames
• Trigonometry
• Linear Algebra

How does wheel motion determine my x-y position and how do I have to move my wheels to get somewhere?
Path Planning

Dijkstra  A*  RRT

What's the shortest path from A to B if I know the map?
Problem: Uncertainty

\[ v = r \phi' \]

Problem: \( \phi' \) subject to uncertainty. Position estimate probabilistic. How to improve it?
Beyond Odometry: Image Processing

Convolution-based Filtering

Thresholding

![Convolution-based Filtering Diagram](image)

![Thresholding Image](image)
Feature extraction

Feature Extraction: Line detection

- Least-squares estimate
- Split-and-Merge
- RANSAC

Raw Date of Laser Scanner

Extracted Lines

\[ \rho_i \cos(\theta_i - \alpha) - r = d_i \]

\[ S_{r,\alpha} = \sum_i d_i^2 = \sum_i (\rho_i \cos(\theta_i - \alpha) - r)^2 \]
Quantifying Noise

Normal distribution

Multi-variate Gaussian

Two noisy observations can be fused to a single observation with lesser variance!
Error Propagation

• Key ideas
  – Every sensor reading has a variance
  – Variances carry forward into measurements
  – Variances are weighted by their impact on the measurement
Markov Localization

- Bayes Rule

\[ P(A|B) = \frac{P(A)P(B|A)}{P(B)} \]

- Perception update:

\[ P(\text{loc}|\text{feat}) = \frac{P(\text{loc})P(\text{feat}|\text{loc})}{P(\text{feat})} \]

- Action update:

\[ P(\text{loc}|\text{odo}) = P(\text{loc}')P(\text{odo}|\text{loc}' \rightarrow \text{loc}) \]
Kalman Filter

- Like Markov Localization, but continuous states (Normal distributions)
- Key idea:
  - Predict what robot *should* see at the estimated position
  - Compare with what it *does* see
  - Calculate in-between position weighted by variances
EKF SLAM
(Simultaneous Localization and Mapping)

• Kalman Filter
  – Position/Orientation
  – Features in the environment

• Re-observation corrects all features
## Summary

<table>
<thead>
<tr>
<th>Topic</th>
<th>Before</th>
<th>After</th>
<th>+6M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward kinematics using basic trigonometry</td>
<td>1.3 ± 60%</td>
<td>3 ± 33%</td>
<td>2.6 ± 53%</td>
</tr>
<tr>
<td>Dijkstra and A* search</td>
<td>1.9 ± 78%</td>
<td>3.3 ± 12%</td>
<td>3.1 ± 12%</td>
</tr>
<tr>
<td>Bayes’ rule</td>
<td>0.8 ± 99%</td>
<td>2.6 ± 20%</td>
<td>2.2 ± 33%</td>
</tr>
<tr>
<td>Convolution</td>
<td>0.6 ± 145%</td>
<td>2.3 ± 38%</td>
<td>2 ± 67%</td>
</tr>
<tr>
<td>Error propagation</td>
<td>0.9 ± 83%</td>
<td>2.5 ± 14%</td>
<td>2.2 ± 30%</td>
</tr>
<tr>
<td>Kalman Filter</td>
<td>0.1 ± 90%</td>
<td>2 ± 39%</td>
<td>1.6 ± 44%</td>
</tr>
<tr>
<td>Simultaneous Localization and Mapping (SLAM)</td>
<td>0.1 ± 152%</td>
<td>2.3 ± 34%</td>
<td>1.85 ± 53%</td>
</tr>
<tr>
<td>Markov Localization</td>
<td>0.14 ± 86%</td>
<td>2.1 ± 22%</td>
<td>1.5 ± 54%</td>
</tr>
<tr>
<td>Inverse kinematics of simple mechanisms</td>
<td>0.9 ± 94%</td>
<td>3 ± 18%</td>
<td>2.5 ± 25%</td>
</tr>
<tr>
<td>Programming in Java</td>
<td>2.19 ± 81%</td>
<td>3.1 ± 15%</td>
<td>3 ± 14%</td>
</tr>
</tbody>
</table>

0: Nothing    2: Get Basic Idea    4: Very Confident

N=21
2nd Semester: Manipulation Challenge

• System design around manipulation

• Previous editions
  – Robot Gardening
  – “Robots building Robots” (ongoing)

• Multi-year activities
Advanced Robotics

• In-depth treatment of “Intro” topics
  – Kinematics of differential wheel -> Kinematics of Cars
  – Forward Kinematics -> Denavit-Hartenberg scheme
  – Inverse kinematics of simple arms -> General inverse kinematics + numerical methods
  – EKF-based SLAM -> Graph based SLAM
  – RRT -> Sampling-based Motion Planning
New hardware
ROS

• Message passing system
• Visualization / Simulation
• Library
  – Hardware drivers
  – Algorithms
• Virtual machine for download

http://correll.cs.colorado.edu/clam/?page_id=21
New Challenges

• Point clouds (RGB + depth)
  – Iterative Closest Point algorithm
  – SIFT features
  – Loop Closure (SLAM)

• Grasping
  – What makes a good grasp? (Coulomb’s Friction Law)
  – How to plan for a good grasp?
New Tasks

• Weekly design reviews
• Write a paper
  – Research hypothesis
  – Heilmeier questions
  – Introduction, Material & Methods, Results, Discussion, Conclusion
• Perform meaningful experiments
  – Null-hypothesis on distributions
  – Test significant difference between distributions
  – Make a significant number of true-false test
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</tr>
</thead>
<tbody>
<tr>
<td>Forward kinematics of manipulating arms</td>
<td>1.2 ± 147%</td>
<td>2.8 ± 13%</td>
</tr>
<tr>
<td>Inverse kinematics of robotic arms</td>
<td>1.1 ± 117%</td>
<td>2.6 ± 9%</td>
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<tr>
<td>Sampling-based motion planning</td>
<td>1.1 ± 117%</td>
<td>2.6 ± 9%</td>
</tr>
<tr>
<td>Scale-invariant feature transformations</td>
<td>0.9 ± 77%</td>
<td>2.2 ± 25%</td>
</tr>
<tr>
<td>Iterative Closest Point (ICP) and RGB-D Mapping</td>
<td>0.5 ± 90%</td>
<td>2.3 ± 27%</td>
</tr>
<tr>
<td>Visual Servoing</td>
<td>0.5 ± 90%</td>
<td>2.1 ± 23%</td>
</tr>
<tr>
<td>Grasping</td>
<td>0.6 ± 73%</td>
<td>2.1 ± 14%</td>
</tr>
<tr>
<td>Graph-based SLAM</td>
<td>1 ± 80%</td>
<td>2.1 ± 14%</td>
</tr>
<tr>
<td>How to write a Research Paper</td>
<td>2.2 ± 35%</td>
<td>2.7 ± 15%</td>
</tr>
<tr>
<td>Statistical Significance Tests</td>
<td>1.8 ± 53%</td>
<td>2.4 ± 18%</td>
</tr>
</tbody>
</table>

0: Nothing    2: Get Basic Idea    4: Very Confident

N=10
Class Debates

- Robots put humans out of work, Robots should be allowed to drive cars, ...
- Argue Oxford style, 10 Pro, 10 Contra, backed up by technical arguments

<table>
<thead>
<tr>
<th>Statement</th>
<th>strongly disagree</th>
<th>disagree</th>
<th>neutral</th>
<th>agree</th>
<th>strongly agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Help me to improve my presentation skills</td>
<td>0.0%</td>
<td>5.9%</td>
<td>41.2%</td>
<td>47.1%</td>
<td>5.9%</td>
</tr>
<tr>
<td>Prepare me for questions that engineers face from society</td>
<td>0.0%</td>
<td>16.7%</td>
<td>11.1%</td>
<td>55.6%</td>
<td>16.7%</td>
</tr>
<tr>
<td>Fundamentally changed my opinion on a topic</td>
<td>11.8%</td>
<td>23.5%</td>
<td>52.9%</td>
<td>11.8%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Are relaxing</td>
<td>0.0%</td>
<td>27.8%</td>
<td>27.8%</td>
<td>38.9%</td>
<td>5.6%</td>
</tr>
<tr>
<td>Let me better understand the technical content of the class</td>
<td>11.1%</td>
<td>16.7%</td>
<td>44.4%</td>
<td>27.8%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Should be part of every class / introduced early in the curriculum</td>
<td>0.0%</td>
<td>29.4%</td>
<td>41.2%</td>
<td>23.5%</td>
<td>5.9%</td>
</tr>
<tr>
<td>Should be replaced by a more in-depth treatment of the technical content</td>
<td>5.9%</td>
<td>35.3%</td>
<td>35.3%</td>
<td>11.8%</td>
<td>11.8%</td>
</tr>
<tr>
<td>Should take less time</td>
<td>11.1%</td>
<td>27.8%</td>
<td>44.4%</td>
<td>5.6%</td>
<td>11.1%</td>
</tr>
<tr>
<td>Should allow for more discussion</td>
<td>0.0%</td>
<td>11.1%</td>
<td>27.8%</td>
<td>55.6%</td>
<td>5.6%</td>
</tr>
<tr>
<td>Reflect up-to-date issues in research and society</td>
<td>0.0%</td>
<td>11.8%</td>
<td>17.6%</td>
<td>29.4%</td>
<td>41.2%</td>
</tr>
</tbody>
</table>

Introduction to Robotics, N=18
Peer-to-Peer Learning in Projects

2008 iteration of “Advanced Robotics” (MIT), N=12
Scalability

• Approach
  – Simulation for many
  – Milestones
  – Experiments on shared platform

• Mainly computing challenges

• Hardware experimentation needs to be requirement
Assessment

• Math-based homework, mid-term and final
• *Systematic, experimental data*
  – Average distance traveled
  – Average computation time
  – ...
• Final presentation / competition/ research paper
• Still unclear how to specify scope of projects
• Portfolio-based assessment with itemized point system
Complexity

• **Approach**
  – Goal-based approach
  – Focus exclusively on software/algorithms
  – Online materials hyperlink to research papers and wikipedia pages

• **Breadth vs. Depth**
  – Deeper learning in the Intro-class
  – Intro topics more cohesive
Summary

• CSCI3302 and CSCI4302/5302 (pending) established
• All course materials online, tools available via Roadnarrows.com, Cyberbotics.com (free for “Ratslife”), ros.org
• Lots of work down the line
  – Reliable simulation environments
  – Improved assessment structure
  – Deeper learning in advanced robotics
  – Improve debate quality
  – ....
References


• [http://correll.cs.colorado.edu](http://correll.cs.colorado.edu)