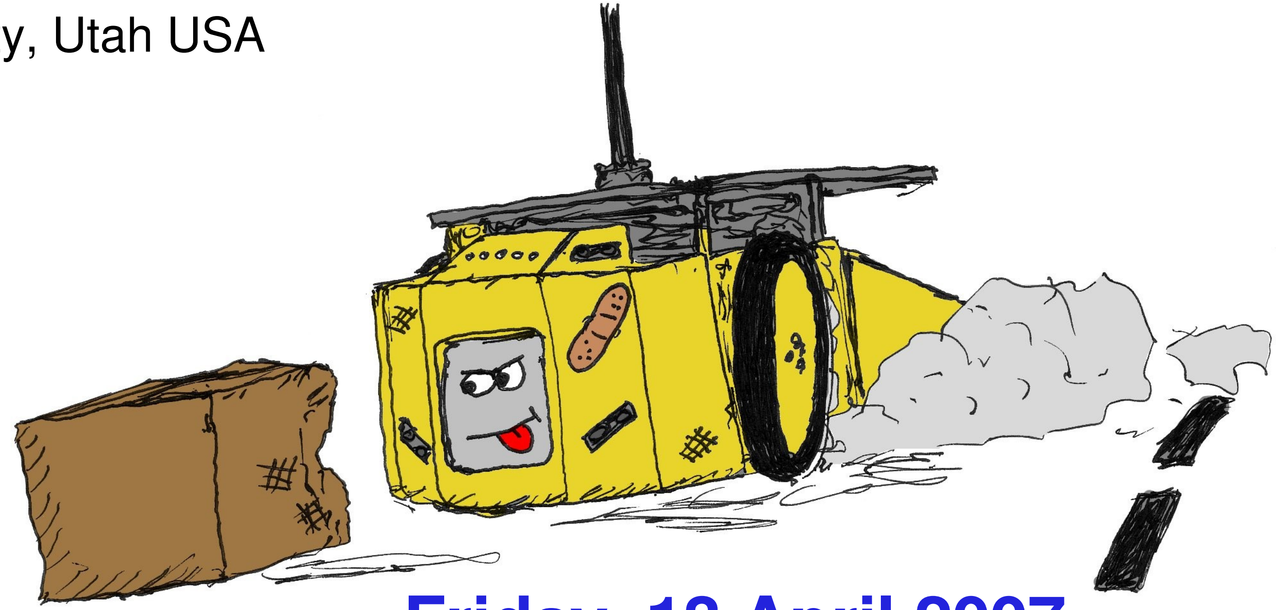
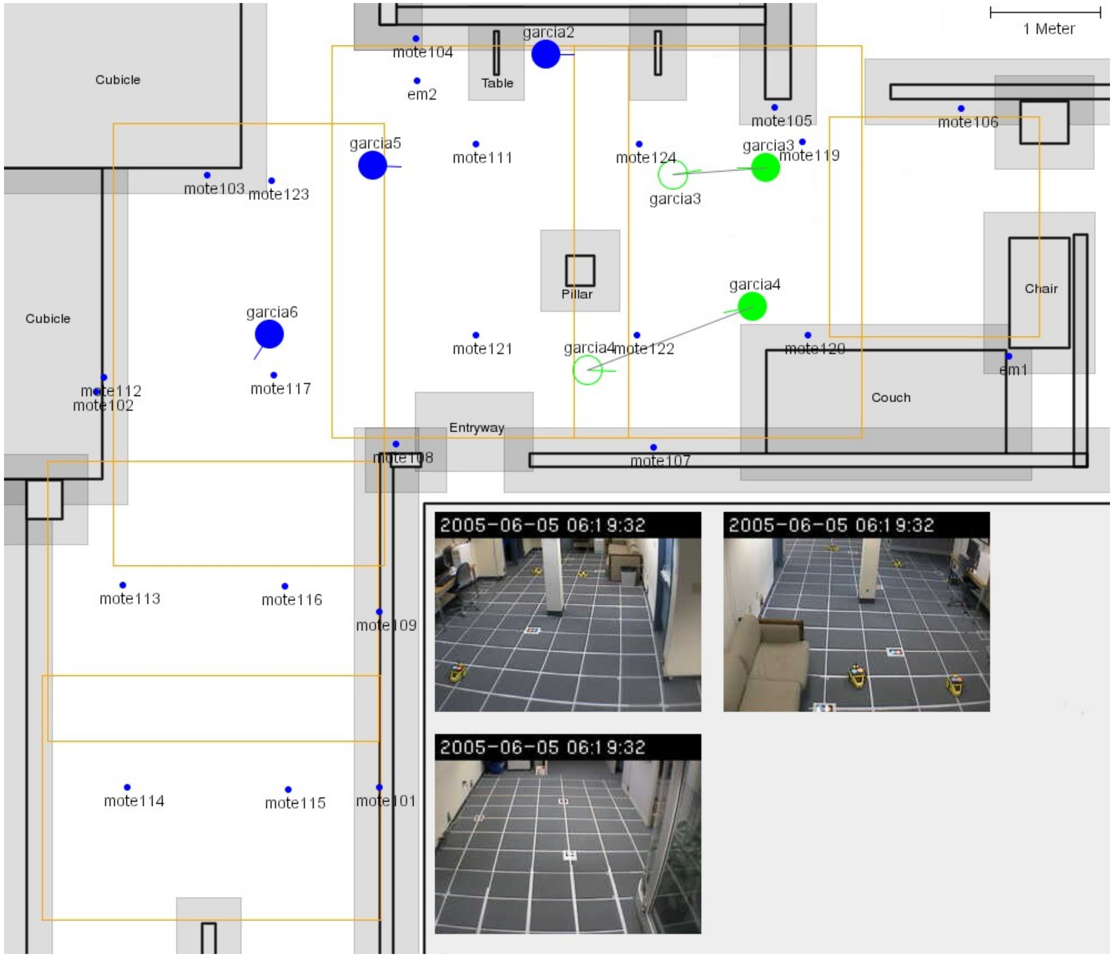
Remote Low Frequency State Feedback Kinematic Motion Control for Mobile Robot Trajectory Tracking

Daniel Montrallo Flickinger
Mark A. Minor
Department of Mechanical Engineering
Flux Research Group, School of Computing
Salt Lake City, Utah USA



Friday, 13 April 2007

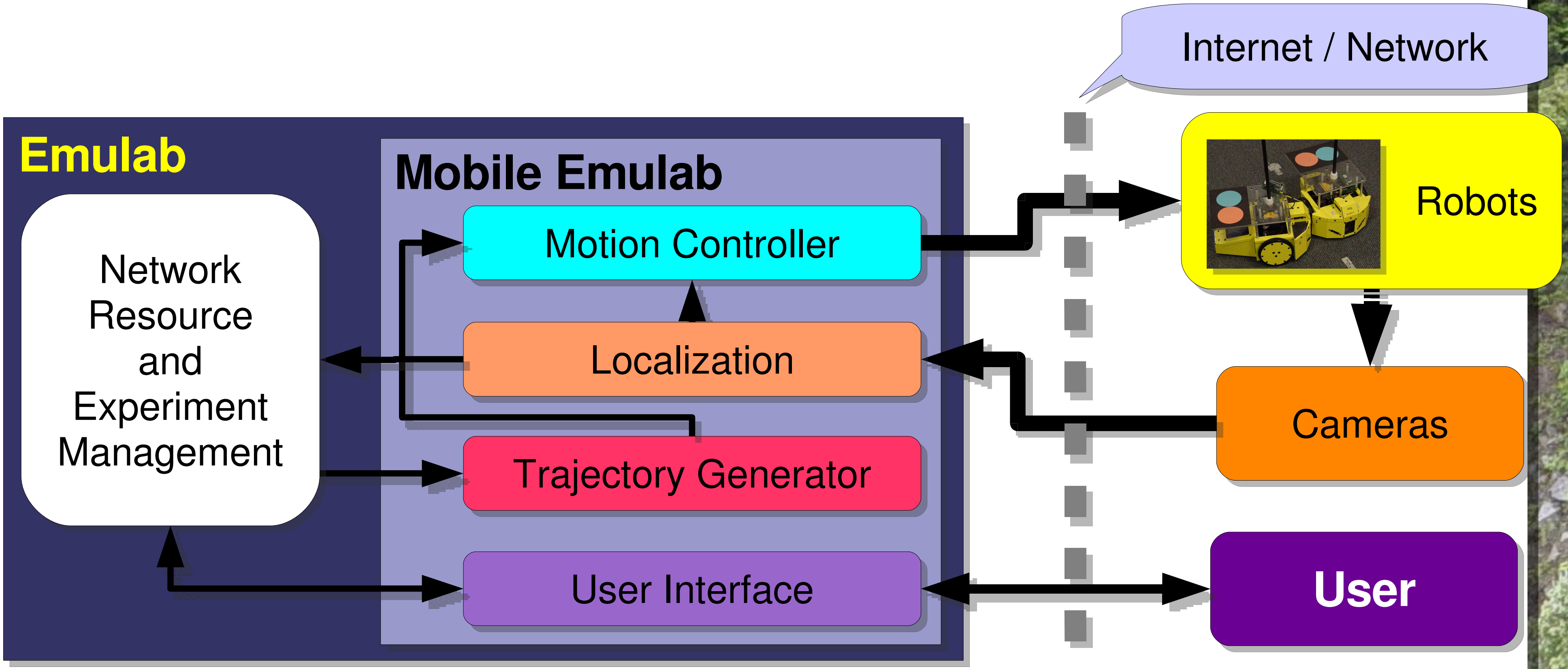
Mobile Emulab



Example of the user control interface

- Mobility is added to Emulab, a wireless research testbed.
- Uses robots to position antennas within a semi-controlled environment
- Publicly available to remote users via the Internet
- Used for wireless network experiments

System Architecture

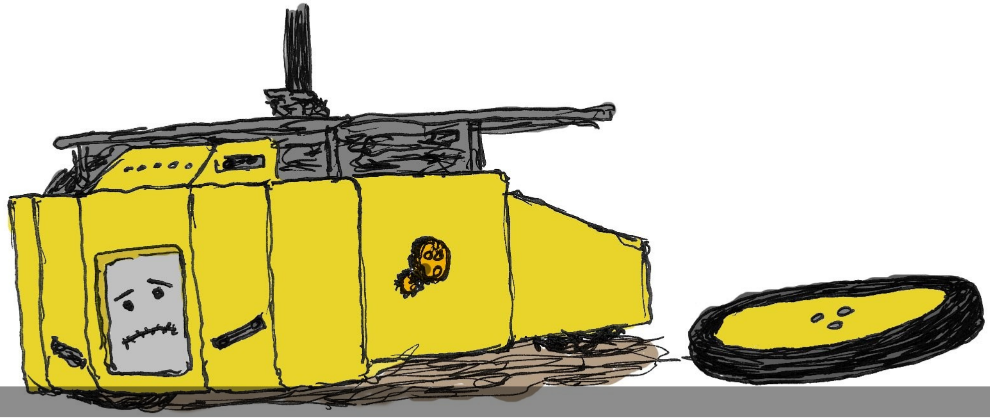


Goals

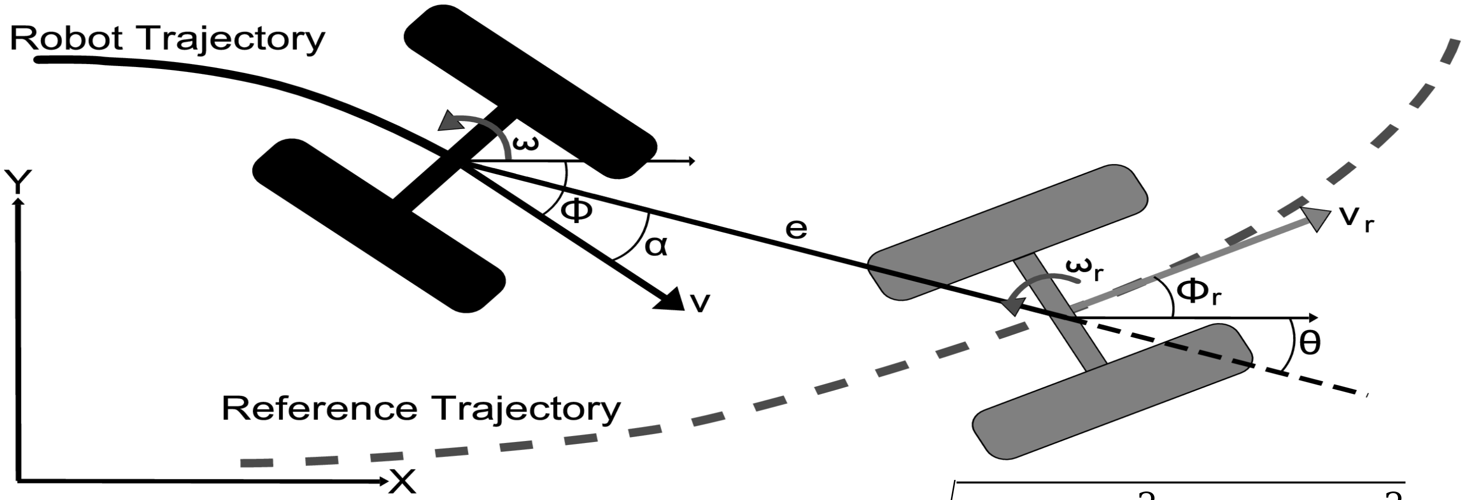
- Teleoperated system that removes the entire motion control structure from the robot, in order to preserve the availability of crucial onboard resources
- Centrally controlled, medium scale mobile robots for wireless networking experiments
- Kinematic motion control at low frequency

Challenges

- The majority of on board computer resources must be kept available for experimenters
- Kinematic control (Built in API to send wheel velocity commands)
- Robots can receive velocity commands at 50 Hz maximum
- Centralized localization system (Odometer drift is significant)
- Localization data limited to 30 Hz, not periodic (Camera hardware cost)



Kinematics



$$e=\sqrt{(x-x_r)^2+(y-y_r)^2}$$

$$\theta=Atan(-y-y_r,-x-x_r)$$

$$\alpha=\theta-\phi+\phi_r$$

- Polar form, which satisfies Brockett's Theorem
- Cartesian to Polar conversion required to obtain polar states

Trajectory Tracking Controller

Controller: (Bounded velocity, curvature.)

$$v_d = \frac{k_1 \cdot e \cdot k_e \cdot \tanh(e - r\sqrt{2} \cdot k_e) + v_r \cdot e \cdot \cos(\theta) \cdot k_e + v_r \cdot r\sqrt{2} \cdot \sin(2\theta) \cdot \left(\sin(\theta) + \frac{\omega_r}{v_r} \cdot e\right)}{e \cdot k_e + r\sqrt{2} \cdot \sin(2\theta) \cdot \sin(\alpha)}$$

$$\omega_d = k_2 \cdot \tanh(\theta + \alpha) + 2\dot{\theta} + \dot{\phi}_r$$

$$k_e = \sqrt{(\zeta - \cos 2\theta)}$$

Dynamic Extension: (Controller outputs become new states.)

$$\dot{v} = -k_v(v - v_d) + \dot{v}_d \qquad \dot{\omega} = -k_\omega(\omega - \omega_d) + \dot{\omega}_d$$

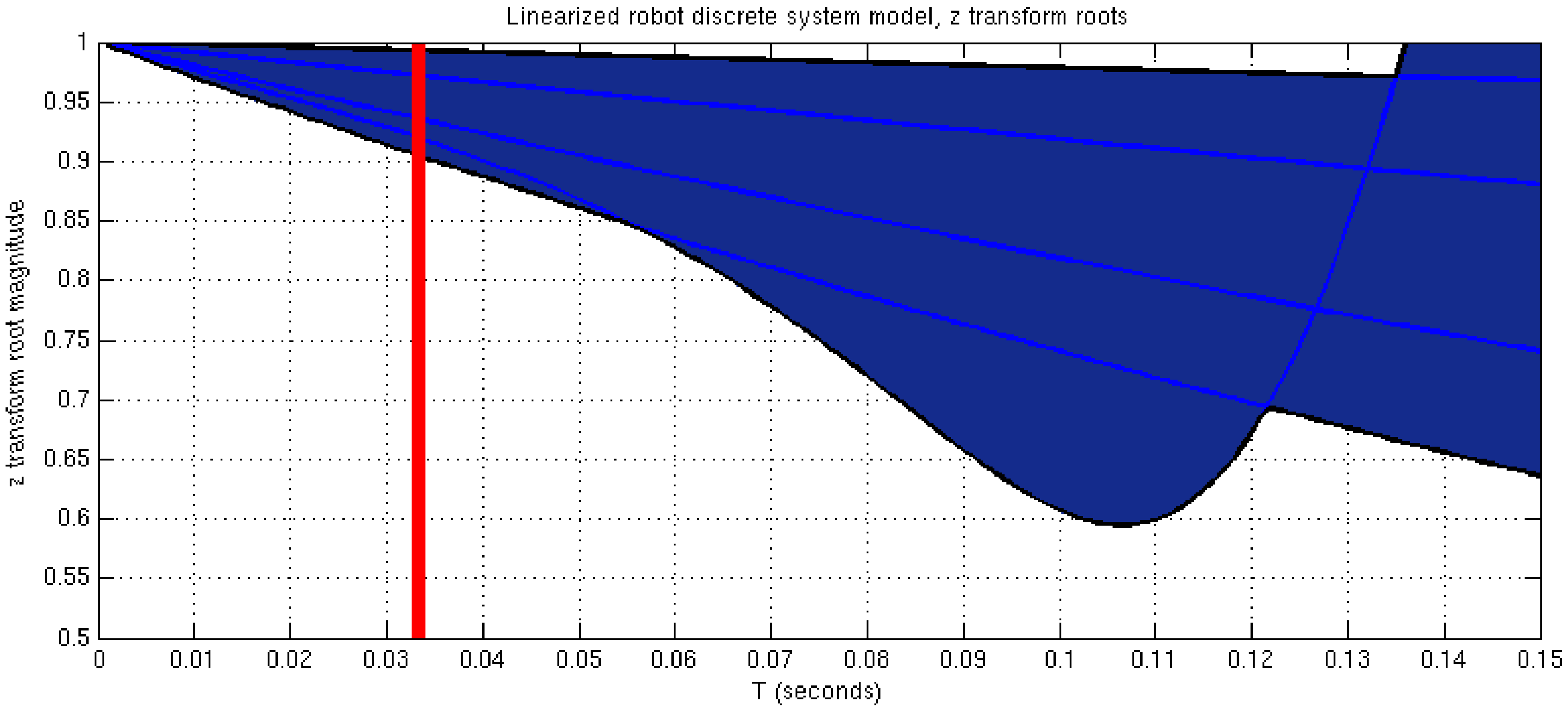
X. Zhu, Y. Kim, and M. A. Minor, “Cooperative distributed robust control of modular mobile robots with bounded curvature and velocity,” in 2005 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Monterey, California, 2005.

Stability Analysis

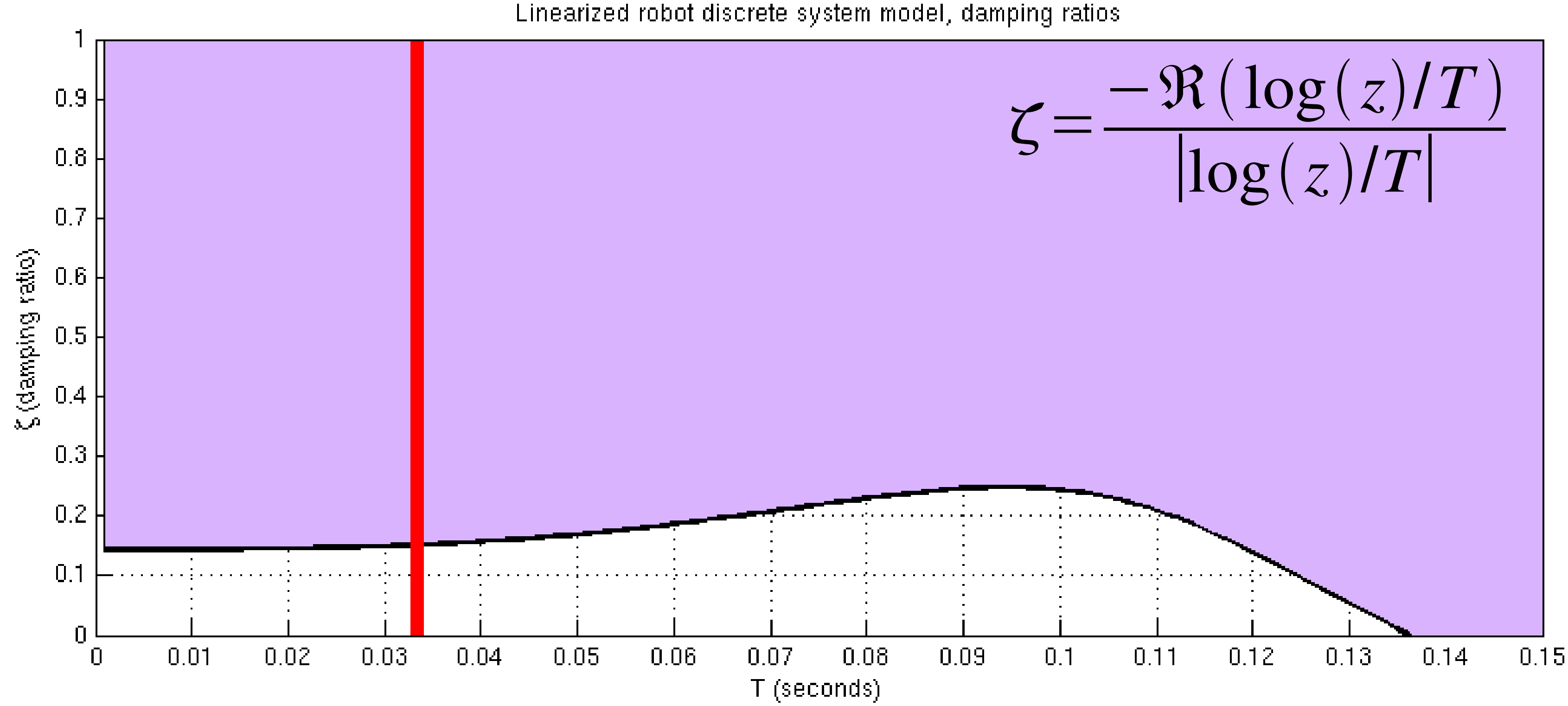
- Define new error states: $e_v = v_r - v_a \quad e_\omega = \omega_r - \omega_a$
- Substitute new states into control laws
- Substitute control laws into kinematic system equations
- Linearize about an equilibrium point (Polar states @ 0, with desired velocity)
- Make the linear system discrete
- Approximate the state transition matrix with a 4th order Taylor series
- Solve for roots, and tune control gains for specified root and damping values

$r = 0.02$ m, $\varepsilon = 0.003$ m, $k_1 = 0.85$,
$k_2 = 0.3$, and $k_v = k_\omega = 3.0.8$

Stability Analysis: Roots



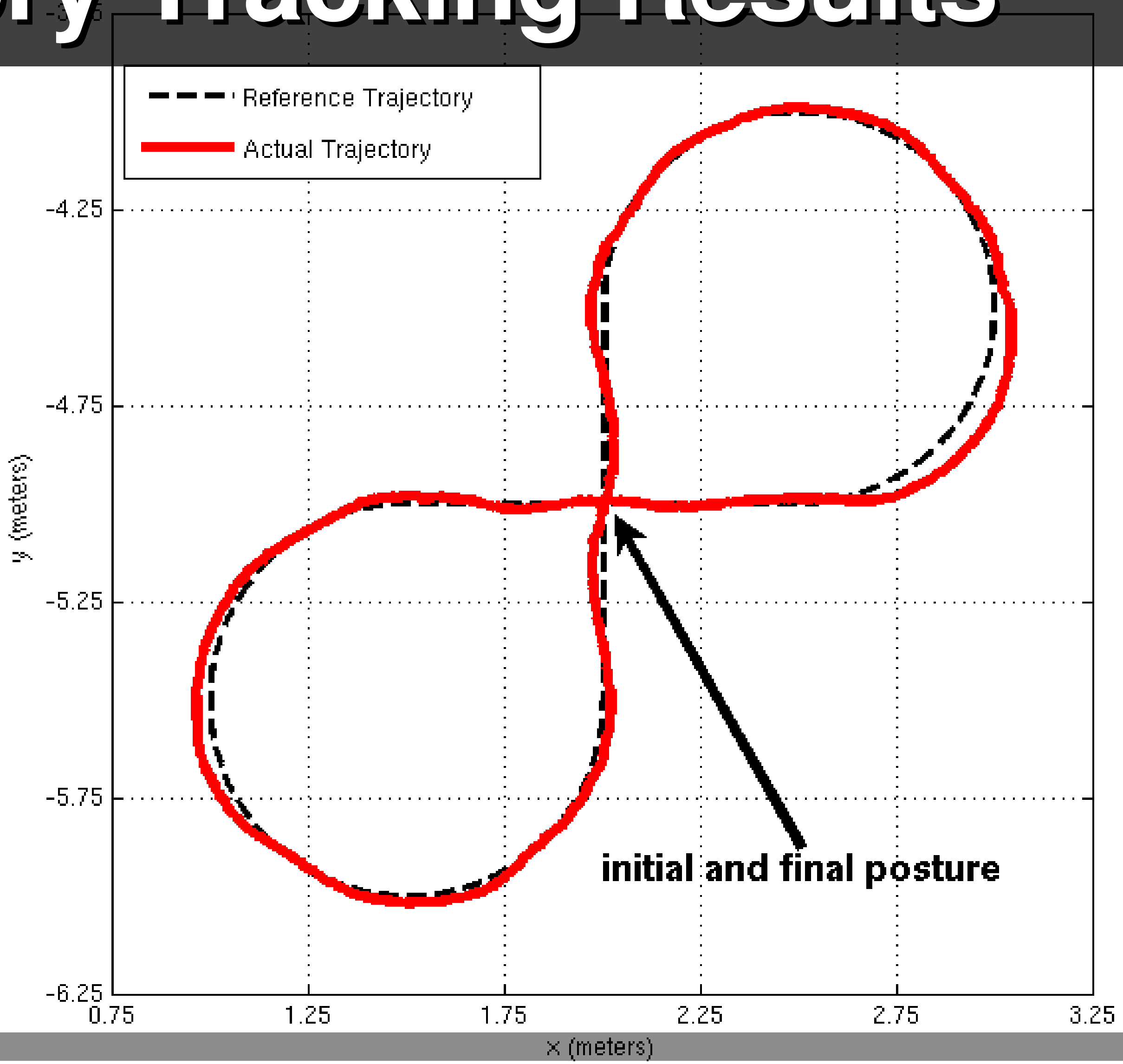
Stability Analysis: Damping Ratio



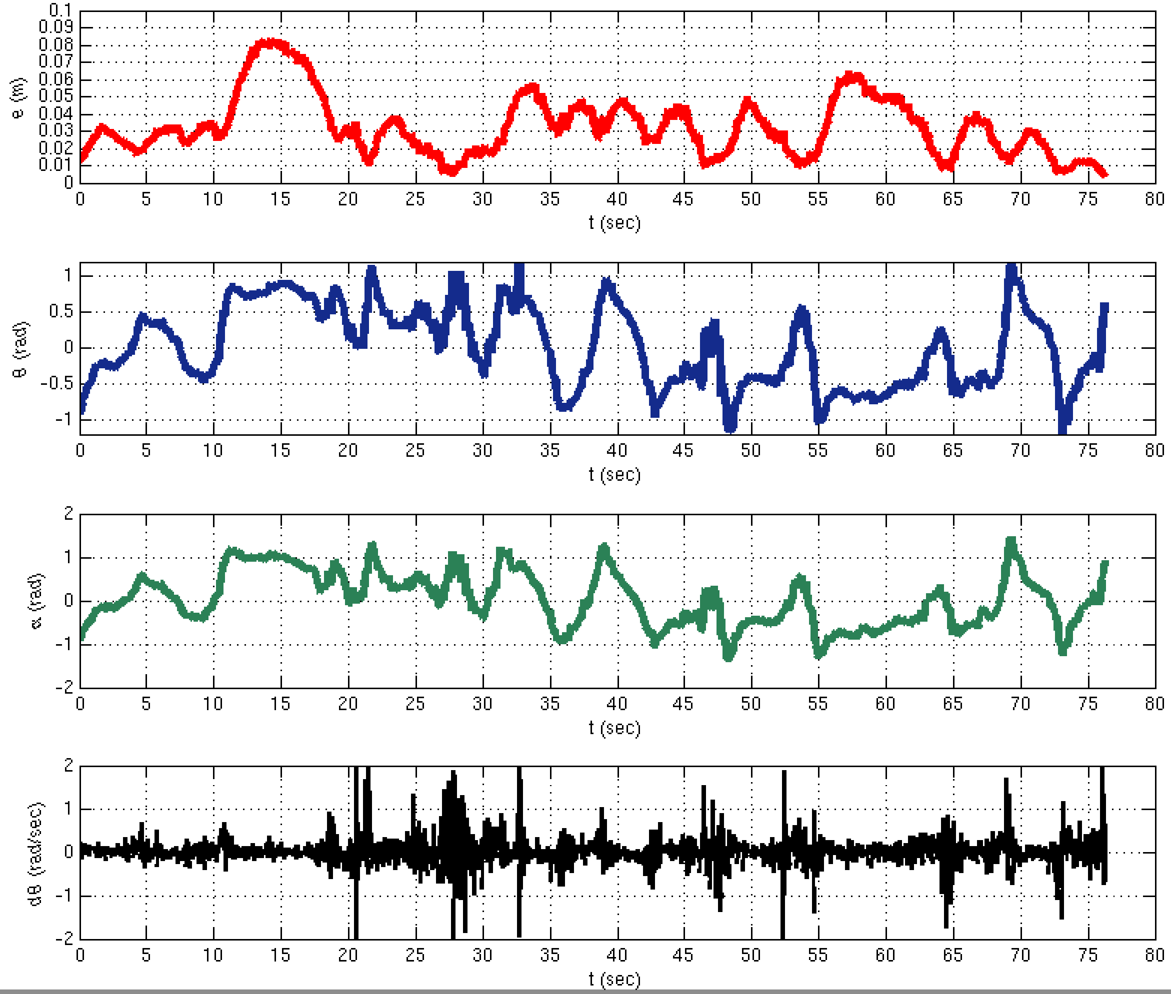
$$\zeta = \frac{-\Re\left(\log(z)/T\right)}{\left|\log(z)/T\right|}$$

Trajectory Tracking Results

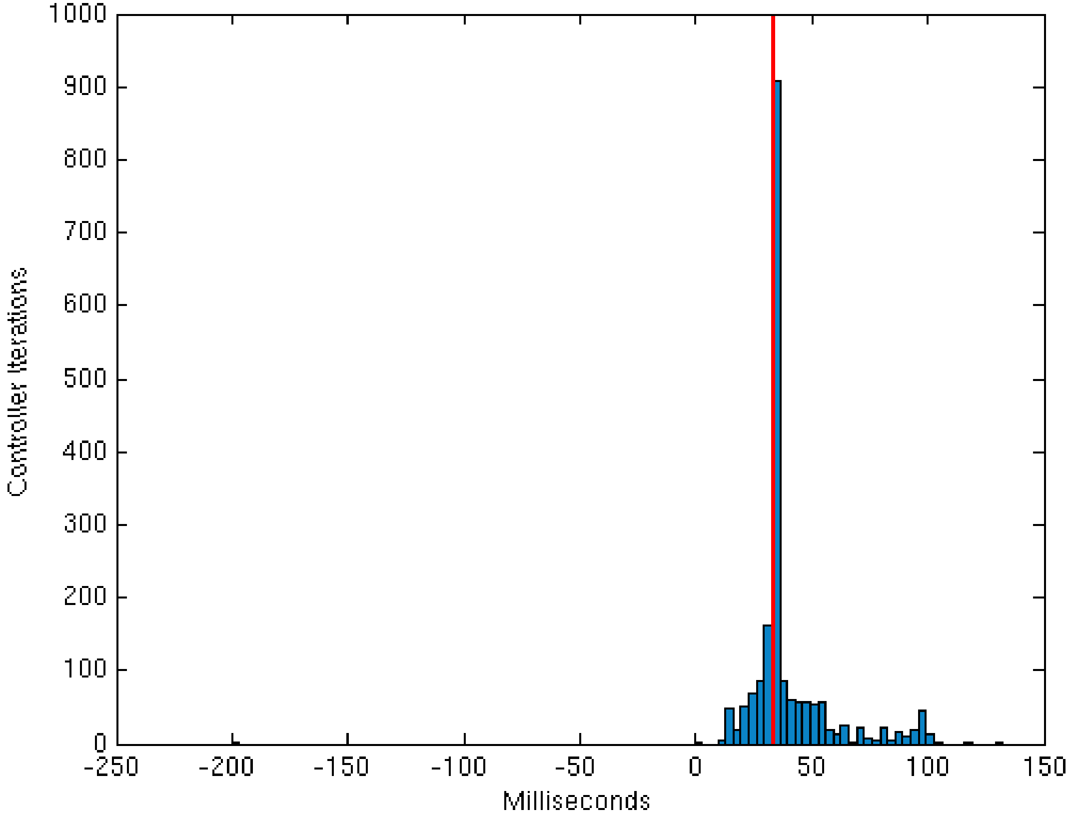
- Tracking error less than 100 mm
- Reference velocity of 0.1 meters per second
- Experiment featured in the video attachment



System Response



Localization Data Frequency



Conclusion

- Kinematic control for wheeled mobile robot trajectory tracking achieved at low sampling frequency
- Stability analysis on discrete linear system for gain tuning
- Motion control over a noncontrolled network

Future Work

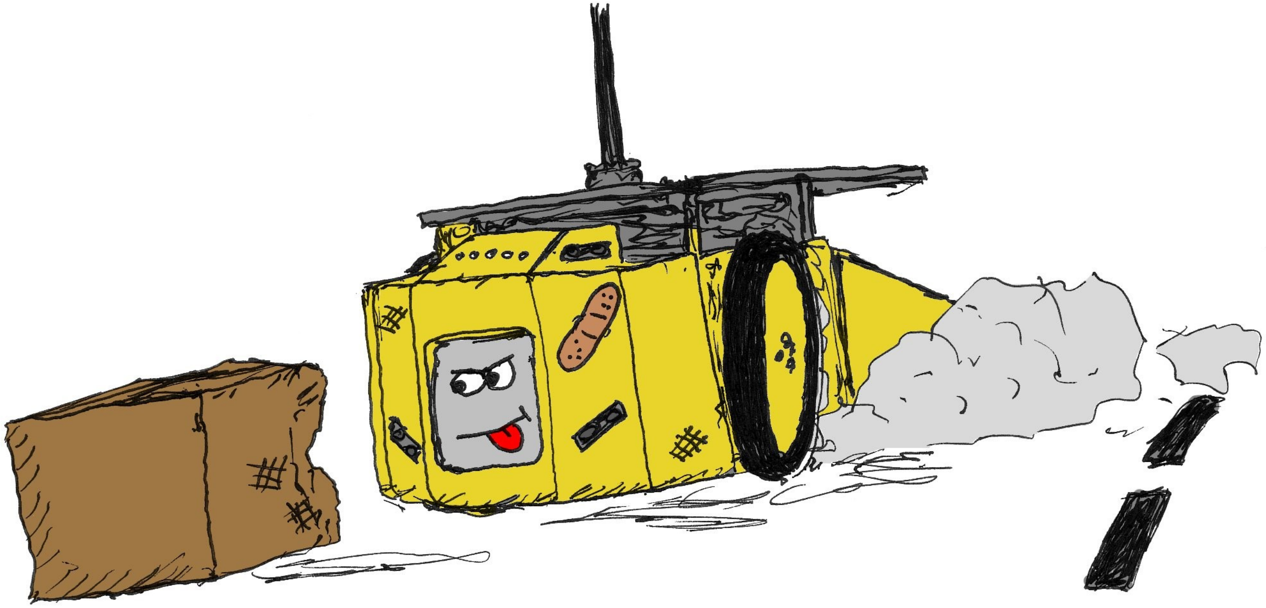
- Design a discrete nonlinear controller instead of adapting a continuous controller
- Implement C^2 continuous trajectories to minimize effects of curvature discontinuities

Acknowledgments

- Thanks to:
  - Mark Minor and Youngshik Kim for help on the discrete system stability analysis
  - Youngshik Kim for the design of the state feedback controller used in this work for trajectory tracking
  - The Flux research group for their work on Emulab and Mobile Emulab, especially David Johnson, Tim Stack, and Russ Fish
- This work is largely sponsored by NSF grants CNS-0335296 and EIA-0321350

Daniel Montrallo Flickinger Daniel.M.Flickinger.4@nd.edu
Mark A. Minor minor@mech.utah.edu

Thank you.



Friday, 13 April 2007