Surface Based Wireless Power Transmission and Bidirectional Communication for Autonomous Robot Swarms

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Overview

• The Swarm Power Problem
• Related Power Distribution Approaches
• Other Wireless Power Systems
• Proposed Power Surface Design
• Proposed Power Surface Characterization
• Conclusions
The Problem
Powering a Swarm of Robots

• Different activity levels = different power consumption
• Primary cell batteries are environmentally unfriendly
• How to maintain rechargeable batteries?

Solution: Get rid of batteries. Provide continuous wireless power to the swarm from its operating surface.

Image Credit: Axelrod, Georgia Tech
Image Credit: Caprari, EPFL Switzerland
Image Credit: McLurkin, MIT
Potential Solutions

• Onboard Power:
  – Batteries
    • Exchange Behaviors
    • Docking Behaviors
  – Alternative Sources
    • Hydrocarbon Fuels
    • Fuel Cells
    • Biomass Fuels

• Offboard Power
  – Tethers
  – Solar, Fields, Kinetic
Proposed Solution

Wireless, battery-less power
(Robots are RFID tags with wheels & sensors)

Ampere’s Law (coil):

\[ H(x) = \frac{I \cdot N_i \cdot r^2}{2 \sqrt{(r^2 + x^2)^3}} \]

Faraday’s Law:

\[ E = \mu_0 H \omega N_p A_p \]

Image Credit: Finkenzeller, "RFID Handbook"
Related Work

Other Inductive Wireless Power Systems

Multiple magnetic induction coils
- Mechanically complex
- Complex control scheme
- Can provide localization info
- Not easily tile-able

Multiple magnetic induction coils
- Mechanically complex
- MEMS and organic FETs
- Complex control scheme
- Can provide localization info
- Tile-able

Image Credit: Gao, Fraunhofer IBMT

Image Credit: Sekitani et al, University of Tokyo
Related Work

Nano-robots powered by fields

- Surface fields cause actuation of nano-actuator
- No logic or memory in the robot
- Better considered “distributed actuator”

NIST Image Credit: Craig McGray
System Design

- 112KHz operating frequency
- Single resonant transmitter coil in power surface
- Non-resonant receiving coil on each robot
- Magnetic flux coupling between transmitting and receiving coils
- Surface to robot coupling virtually unaffected by number of robots
- Mechanically and electrically simple
- Supports bidirectional communication
- Does not support localization
Resonance Considered

Advantage of Resonant Coils:
High Q increases circulating current in transmitting coil for given drive voltage - yields higher induced voltage in robot

\[ H(x) = \frac{I N_t \cdot r^2}{2 \sqrt{(r^2 + x^2)^3}} \quad E = \mu_0 H \omega N_p A_p \]

Disadvantages of Resonant Coils:
High Q coils present manufacturing problems
Coupled resonant coils interact and de-tune each other
High Q resonances limit available bandwidth for communication

Tradeoff:
Use resonant transmitting coil under surface
Robots use non-resonant receiving coils
Robots interact with surface resonance, but not each other
Power Surface Design

Schematic

Underside of Prototype
(0.6m x 0.6m)

Primary

Resonant Secondary

L=740uH
C=2.7nF
F=112KHz
Robot Power Design

Logic Power High Priority
Motor Power Lower Priority

Schematic

Communications & Power Conditioning Board
Robot Prototype

Line-Following Application

PIC microcontroller
ESCAP DC gearmotors
IR line sensor array
IR Comm.
Coil
Communication

Surface-to-Robot

- 100% AM modulation
- Data rate 800bps, limited by coil Q of 125
Communication

Surface-to-Robot at 800 bps

Coil resonance limits rise time / data rate

Surface Field Amplitude-Modulated

Robot Filtered RX

Robot RX Data
Communication

Robot-to-Surface

- Load modulation by FET switch
- Data rate 20Kbps, 1% modulation depth
Communication

Robot-to-Surface at 20 kbps

Robot TX Data

Surface DEMOD input

Surface DEMOD output
Power Density

Measured Power (Watts) into simulated robot load (80 Ω) at various heights above surface

0 cm (on surface)  5 cm above surface

> 4.1mW/cm² average
Power Density

Measured Power (Watts) into simulated robot load (80 Ω) at various heights above surface

10 cm above surface

15 cm above surface
Robot-Robot Interaction

Non-Resonant Coils on Robots

Virtually no interaction between robot coils until they’re atop each other.

Overlapping coils interact

Non-overlapping = little interaction
System Efficiency

\[ \eta_{\text{system}} \approx \frac{n \cdot 200\text{mW}}{12\text{W} + n \cdot 200\text{mW} \cdot \eta_{\text{coupling}}} \]

Small when robot coils are small compared to surface

- Surface quiescent draw is 12W to overcome losses in transmitting coil.
- Each robot recovers ~200mW
- Efficiency increases with # of robots
Summary

Benefits:
- Simple, Low Cost Construction
- Persistent Power to Large Number of Robots
- Bidirectional Communication
- Enabling Technology for Swarm Research

Future Work:
- Characterize Efficiency with Larger Number of Robots
- Improve Communication Bandwidth
- Develop Tiling Scheme
- Web Community for Interested Researchers
Questions?

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