Indoor Robot Localization and Mapping using ZigBee Radio Technology

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Objective and Contribution

Objective

- Design and implement a cost–effective, easy to use, and modular system to localize a mobile robot and map an indoor environment

Contribution

- A full-fledge robot navigation (localization and motion control) and mapping algorithm is designed and implemented
- Hardware and software architectures are cost–effective and easy-to-implement
- Range-only measurements are used to estimate the robot's pose and the positions of the radio sources (range-only mapping)
- Computational implementation of the proposed algorithm is performed in the commercial robot simulator, V-REP

Problem Setup

- A set of waypoints on the ground define the mobile robot's path
- XBee radio sources are dispersed in the robot's operating environment
- Mobile robot must simultaneously localize itself and map the XBee radio positions (SLAM) while navigating through the set of waypoints

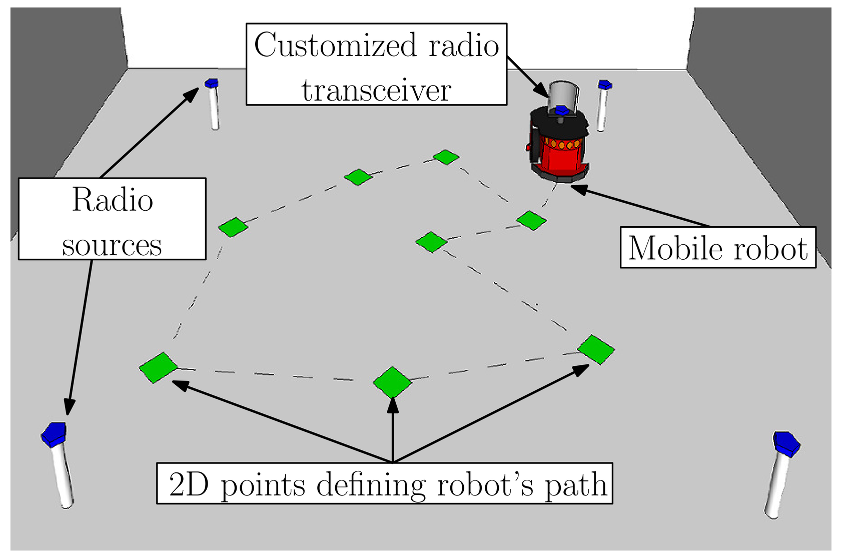


Figure 1: High level setup of the system

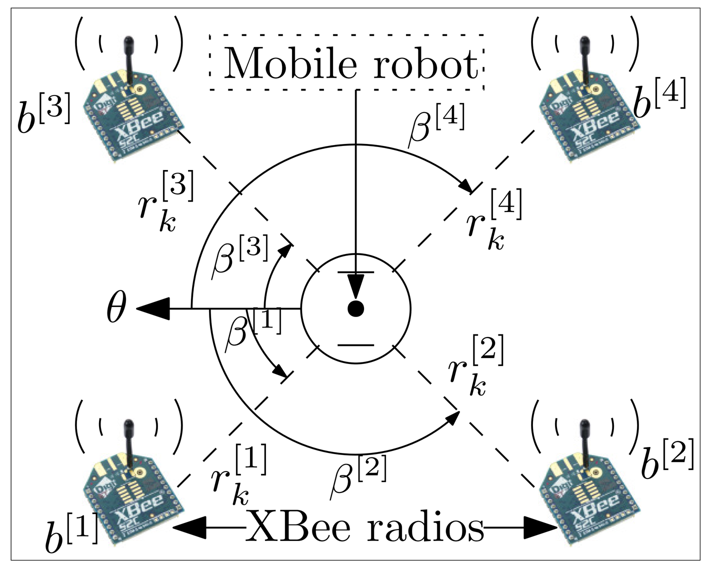


Figure 2: Network of radio sources and mobile robot.

EKF-SLAM

- The Extended Kalman Filter Simultaneous Localization and Mapping (EKF-SLAM) is a popular algorithm used in mobile robotics due to its resilience in noisy environments
- EKF-SLAM prediction step

$$\hat{\mathbf{q}}_{k+1}^{-} = \hat{\mathbf{q}}_{k}^{+} + \mathbf{C}^T \mathbf{f}_r(\hat{\mathbf{q}}_{k,r}^{+}, \mathbf{u}_k, \mathbf{0}), \quad (1a)$$
$$\mathbf{P}_{k+1,rr}^{-} = \mathbf{F}_k \mathbf{P}_{k,rr}^{+} \mathbf{F}_k^T + \mathbf{L}_k \mathbf{Q}_k \mathbf{L}_k^T, \quad (1b)$$
$$\mathbf{P}_{k+1,r\mathcal{B}}^{-} = \mathbf{F}_k \mathbf{P}_{k,r\mathcal{B}}^{+}, \quad (1c)$$
$$\mathbf{P}_{k+1,\mathcal{B}r}^{-} = \left(\mathbf{P}_{k+1,r\mathcal{B}}^{-}\right)^T \quad (1d)$$

- EKF-SLAM update step

$$\mathbf{S} = \left[\mathbf{H}_r \ \mathbf{H}_{\mathbf{b}^j}\right] \begin{bmatrix} \mathbf{P}_{k+1,rr}^{-} & \mathbf{P}_{k+1,r\mathbf{b}^j}^{-} \\ \mathbf{P}_{k+1,\mathbf{b}^j r}^{-} & \mathbf{P}_{k+1,\mathbf{b}^j\mathbf{b}^j}^{-} \end{bmatrix} \begin{bmatrix} \mathbf{H}_r^T \\ \mathbf{H}_{\mathbf{b}^j}^T \end{bmatrix} + \mathbf{R}, \quad (2a)$$
$$\mathbf{K}_{k+1} = \begin{bmatrix} \mathbf{P}_{k+1,rr}^{-} & \mathbf{P}_{k+1,r\mathbf{b}^j}^{-} \\ \mathbf{P}_{k+1,\mathcal{B}r}^{-} & \mathbf{P}_{k+1,\mathcal{B}\mathbf{b}^j}^{-} \end{bmatrix} \begin{bmatrix} \mathbf{H}_r^T \\ \mathbf{H}_{\mathbf{b}^j}^T \end{bmatrix} \mathbf{S}^{-1}, \quad (2b)$$
$$\hat{\mathbf{q}}_{k+1}^{+} = \hat{\mathbf{q}}_{k+1}^{-} + \mathbf{K}_{k+1}\mathbf{v}, \quad (2c)$$
$$\mathbf{P}_{k+1}^{+} = \mathbf{P}_{k+1}^{-} - \mathbf{K}_{k+1}\mathbf{S}\mathbf{K}_{k+1}^T, \quad (2d)$$

Range and Bearing Approximation

- A customized radio transceiver (CRT) was built to determine the range and bearing of XBee radios (beacons) in the robot's environment
- A set of received signal strength indicator (RSSI) measurements from each XBee radio is collected as the parabolic reflector rotates 360°
- Equation to convert RSSI to range r_k

$$r_k = 10^{\frac{|\mathrm{RSSI}| - |P_{\mathrm{ref}}|}{10\eta}}$$

- Bearing β^j of an XBee radio is determined to be the angle turned by the reflector where the strongest RSSI is measured

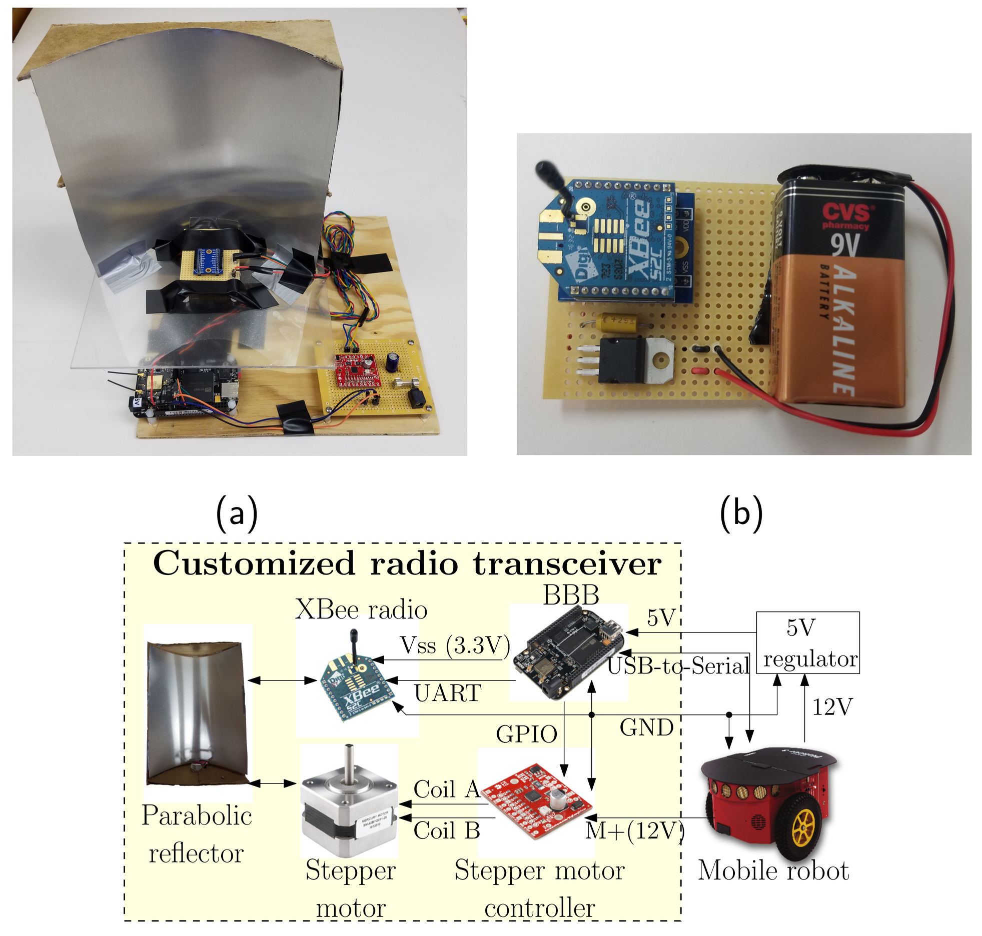


Figure 3: (a) Customized radio transceiver, (b) a XBee radio beacon, and (c) the CRT's interconnections.

Motion Control Strategy

- Implemented using a proportional (P) controller and a fuzzy logic controller.
- P controller uses a proportional constant to update the robot's steering angle γ_k as it approaches a waypoint (denoted as $p^{[i]}$) in its path, $\Delta\gamma_k = \gamma_k^{\text{new}} - \gamma_k^{\text{old}}$
- Fuzzy logic controller uses human like reasoning to determine the robot's linear speed ν_k without requiring accurate approximate distances ρ_k between the robot and it's current waypoint
- Two control inputs to the robot are linear speed ν_k and angular velocity ω_k, converted from γ_k in post-processing

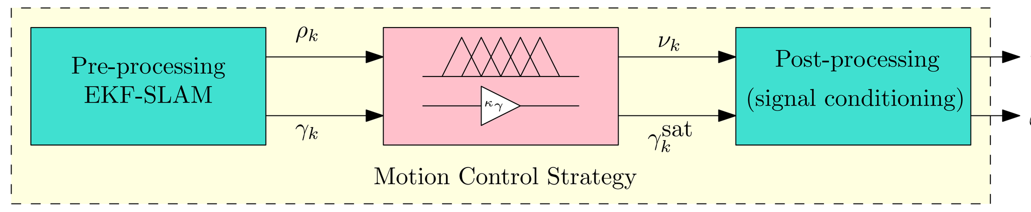
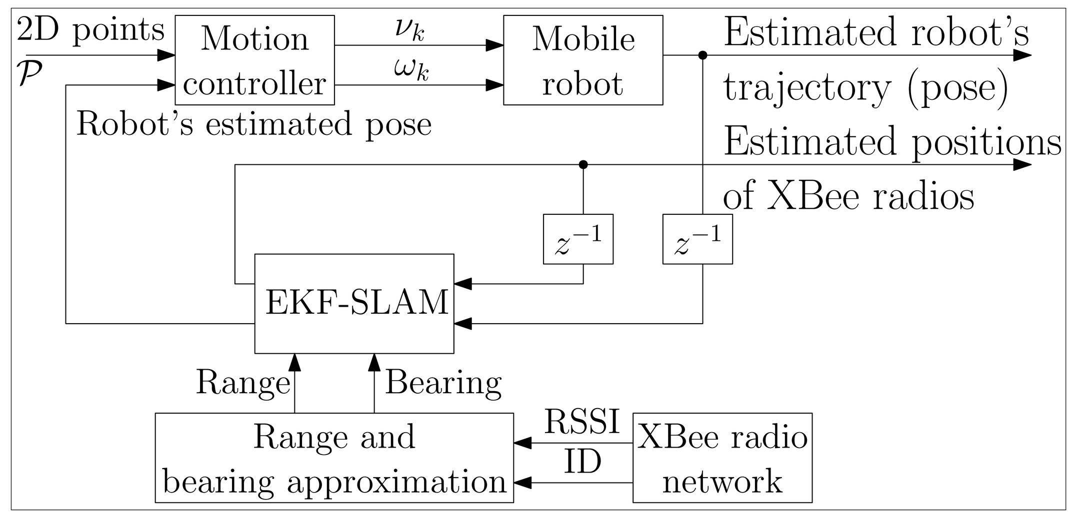


Figure 4: Implemented motion control strategy

Subsystem Block Diagram



V-REP Simulation

- Algorithm simulated using V-REP
- Offers a variety of robot models for testing
- Can accurately and consistently produce results like those expected in real–world scenarios due to physics modeling for the specific robot and its environment

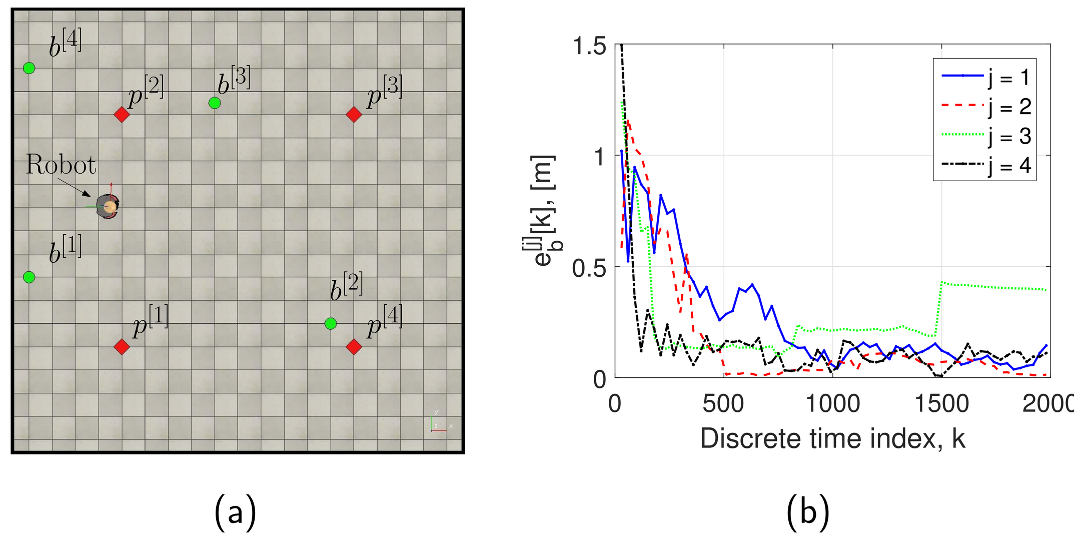


Figure 5: (a) Screenshot taken during V-REP simulation and (b) beacon position estimation error over iterations.

Experimental Results

- Performance is tested using Pioneer 3-DX in lab environment containing metal cabinets and other obstacles which can increase noise
- Four beacons are distributed throughout robot's workspace
- The Robot Operating System (ROS) is used for modularity and ease of communication between subsystems
- Performance is monitored in real–time from a remote location

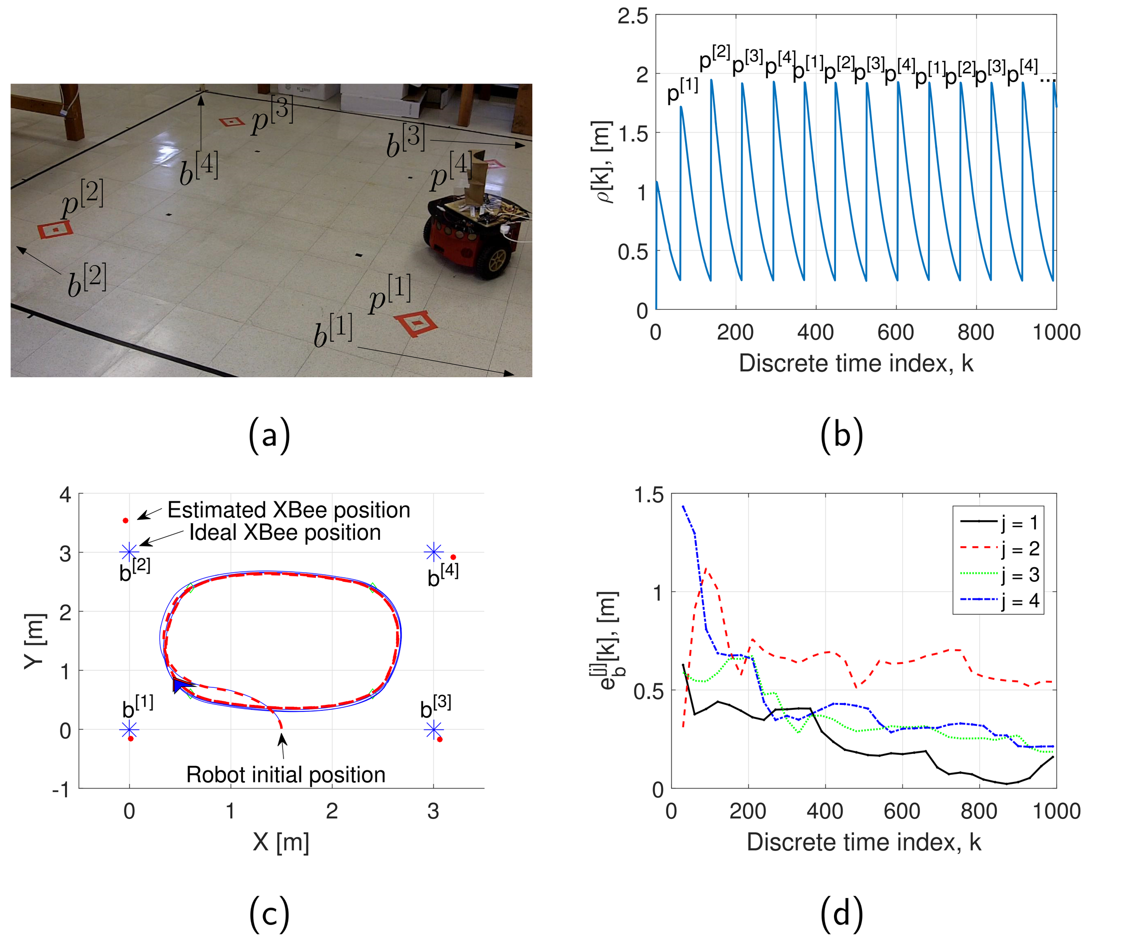


Figure 6: (a) The robot's configuration at $t = 25$ s. (b) Estimated distance to waypoint over time, (c) final trajectory of the robot and (d) the beacon position estimation error.

- Beacon position estimation error is decreasing as the robot navigates through each waypoint
- Some periodic increases in error from the nature of environment and RF signal multipath

Conclusion and Future Work

- Experimental performance is satisfactory with respect to the noisy environment
- Low–cost (around \$140 for the customized radio transceiver and \$23 for each beacon)
- Easily adaptable to other mobile robots
- System can be applied in low-visibility since there is no reliance on vision-based sensors
- Bearing-only measurement model can be researched for localization and mapping in an underwater environment