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Computer Vision-assisted Battery-free RFID Systems for Object Recognition, Localization and Orientation

by Zhongqin Wang

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of Min Xu

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Certificate of Original Authorship

I, Zhongqin Wang declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Electrical and Data Engineering, Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis. This document has not been submitted for qualifications at any other academic institution.

Also, I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of the requirements for a degree at any other academic institution except as fully acknowledged within the text. This thesis is the result of a Collaborative Doctoral Research Degree program with Nanjing University of Posts and Telecommunications, China.

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ABSTRACT

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by
Zhongqin Wang
Supervisor: Dr. Min Xu

Battery-free radio frequency identification (RFID) is a promising technique in Internet of Things (IoT) applications that use wireless signals to identify a physical object from its attached RFID tag. Compared to the existing barcode identification systems, RFID can still work in the non-line-of-sight (NLOS) scenarios that some obstructions block the identifier. Recently, many researchers start regarding each RFID tag as a battery-free sensor, whose indicator is the backscatter signal fingerprint reported by an RFID reader. Since the sensor could sense the change in the position and orientation of an RFID tag relative to a reader antenna as well as surroundings, a variety of battery-free RFID sensing systems are proposed for object localization, direction tracking, material recognition, human breathing/heartbeat rate assessment, liquid leakage detection, etc. However, some technical challenges still remain to be addressed in these purely RFID-based systems. This thesis introduces computer vision (CV) techniques into RFID systems to minimize the impact of RF phase periodicity and multipath interference. In the thesis, three categories of CV-assisted battery-free RFID systems for object recognition, localization and orientation are designed, and the main contributions include:

1) This thesis presents RF-Focus, a CV-assisted system that recognizes moving RFID-tagged objects within the region of interest and tracks their trajectories in multipath environments. To achieve RF-Focus, novel RSSI/RF phase-distance models with additional multipath terms compared to traditional models are proposed to characterize the impact of multipath interference, and thereby a dual-reader-antenna solution is designed to deal with it. Moreover, the multipath terms in RSSI and RF phase can be leveraged to clean the phase shift caused by frequency-dependent RFID hardware characteristics in RF phase. After that, an innovative fusion algorithm is designed to match position proposals outputted by a 2D camera and the cleaned RF phase for object recognition. In the experiments, RF-Focus achieves 91.67% ROI object recognition in multipath environments when simultaneously tracking five moving objects.

2) This thesis proposes RF-MVO, a CV-assisted system that locates stationary RFID tags in 3D space without driving a platform carrying reader antennas along a predefined trajectory or pre-deployed track. To achieve RF-MVO, a 2D camera is affixed to reader antennas. A fusion model is designed to fuse camera trajectory in the camera view with depth-enabled RF phase to achieve real-world trajectory transformation and tag DOA estimation. On this basis, a novel 3D localization is

proposed, which could avoid consuming huge computations to search for all possible regions. In addition, a joint optimization algorithm is designed to accelerate RF-MVO and improve its estimation accuracy. Finally, this thesis introduces horizontal dilution of precision widely used in satellite positioning systems to find out the optimal localization result. The experiments show that RF-MVO achieves 6.23cm localization accuracy in 3D space.

3) This thesis proposes RF-Orien3D, a CV-assisted system that leverages the variation of each tag radiation pattern in a two-RFID-tag array to estimate a labeled object's spatial directions (i.e., azimuth and elevation) in multipath environments. To achieve RF-Orien3D, this work proposes novel RSSI/RF phase-distance models when tag mutual coupling and multipath interference both occur. In the models, one variable to be estimated is tag radiation pattern, which is simulated by building a two-tag array from a 2D image; another is modulation factor, which is estimated using RFID fingerprints in non-coupling and coupling in free space. On this basis, a convolutional neural network (CNN)-based method is proposed by simulating all multipath impacts on RFID fingerprints based on the proposed fingerprint models to pre-train a CNN and then collecting measured data to fine-tune the CNN for 3D orientation. In the experiments, RF-Orien3D achieves median angle errors of 29° and 11° in azimuth and elevation.

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List of Publications

Conference Papers

C-1. **Zhongqin Wang**, **Min Xu**, Ning Ye, Ruchuan Wang, Haiping Huang and Fu Xiao, "RF-Mirror: Mitigating Mutual Coupling Interference in Two-Tag Array Labeled RFID Systems", *Proc. of IEEE International Conference on Sensing, Communication and Networking(SECON)*, pp. 1-9, 2020. **(CORE B, Acceptance Rate: 27.9% (36/129))**

C-2. **Zhongqin Wang**, **Min Xu**, Ning Ye, Ruchuan Wang and Haiping Huang, "RF-Focus: Computer Vision-assisted Region-of-interest RFID Tag Recognition and Localization in Multipath-prevalent Environments", *Proc. ACM Interactive, Mobile, Wearable and Ubiquitous Technologies*, Vol. 3, No. 1, Article 29, 2019. **(UbiComp 2019, CORE A*)**

C-3. **Zhongqin Wang**, **Min Xu**, Ning Ye, Ruchuan Wang and Haiping Huang, "RF-MVO: Simultaneous 3D Object Localization and Camera Trajectory Recovery Using RFID Devices and a 2D Monocular Camera", *Proc. IEEE International Conference on Distributed Computing Systems (ICDCS)*, pp. 534-544, 2018. **(CORE A, Acceptance Rate: 20% (78/378))**

Journal Papers

J-1. **Zhongqin Wang**, **Min Xu**, Ning Ye, Ruchuan Wang, Haiping Huang and Fu Xiao, "Computer Vision-assisted 3D Object Localization via COTS RFID Devices and a Monocular Camera," *IEEE Transactions on Mobile Computing (TMC)*, 2019, doi: 10.1109/TMC.2019.2954830. **(CORE A*)**

Contents

List of Figures

Abbreviation

RFID-Radio Frequency Identification
IOT-Internet of Things
RF-Radio Frequency
EPC- Electronic Product Code
LOS-Line of Sight
RSSI-Received Signal Strength Indication
mmWave-millimetre Wave
CV-Computer Vision
ROI-Region of Interest
MVO-Monocular Visual Odometry
DOA-Direction of Arrival
HDOP-Horizontal Dilution of Precision
CTFs-Channel Transfer Functions
CNN-Convolutional Neural Network
COTS-Commercial Off-the-Shelf
NLOS-Non-Line-of-Sight
CW-Continuous Wave
ASK-Amplitude Shift Keying
PSK-Phase Shift Keying
PR-ASK-Phase-reversal Amplitude Shift Keying
DSB-ASK-Double Sideband-Amplitude Shift Keying
AOA-Angle of Arrival
GMMs-Gaussian Mixture Models
NTP-Network Time Protocol
2D-2 Dimensional
3D-3 Dimensional
VO-Visual Odometry
GPS-Global Positioning System
FPS-Frames Per Second
SVD-Singular Value Decomposition
LTK-Low-Level-Reader-Protocol Toolkit
SLAM-Simultaneous Localization and Mapping