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Radar-Camera Infrastructure for Automotive Safety

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FINAL REPORT

August 5, 2024

1. Report No. N/A	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle Radar-Camera Infrastructure for Automotive Safety	**5. Report Date** Aug 5, 2024
	6. Performing Organization Code CMU
7. Author(s) Swarun Kumar, Ph.D., https://orcid.org/0000-0002-5398-5347	**8. Performing Organization Report No.** **N/A**
9. Performing Organization Name and Address CMU, 5000 Forbes Ave Pittsburgh PA 15213	**10. Work Unit No.**
	11. Contract or Grant No. Federal Grant No. 69A3552344811
12. Sponsoring Agency Name and Address Safety21 University Transportation Center Carnegie Mellon University 5000 Forbes Avenue Pittsburgh, PA 15213	**13. Type of Report and Period Covered** Final Report (July 1, 2023-June 30, 2024)
	14. Sponsoring Agency Code USDOT

15. Supplementary Notes

16. Abstract

This project develops a high-resolution imaging system despite obstructions using a mmWave radar coupled with other visual sensing systems. We specifically focus on single-chip automotive mmWave radars that are widely deployed in cars as collision sensors, yet are extremely compact – merely centimeters across. Our key technical insight is that both the mmWave radar and camera have complementary strengths. While the mmWave radar offers extremely high depth-resolution (centimeter-scale at even hundreds of meters) and through-occlusion imaging, its spatial resolution is extremely poor (several degrees). Our work explores mechanisms to achieve high resolution radar on a single combined platform, coupled with visual sensing and a variety of signal processing and learning strategies.

17. Key Words Mobile systems	**18. Distribution Statement** No restrictions.

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 4	**22. Price**

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Radar-Camera Infrastructure for Automotive Safety

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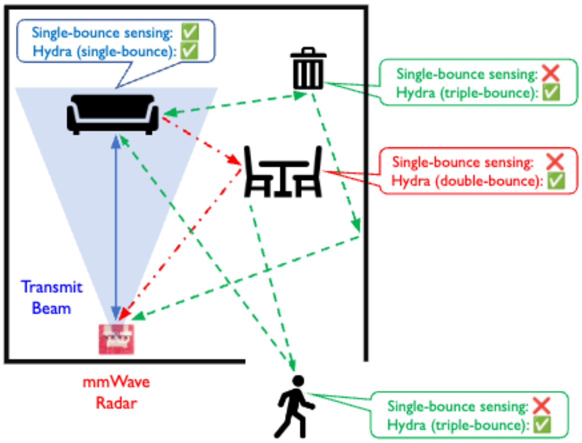
Annual Project Report

Problem

This project develops a high-resolution imaging system despite obstructions using a mmWave radar coupled with other visual sensing systems. We specifically focus on single-chip automotive mmWave radars that are widely deployed in cars as collision sensors, yet are extremely compact – merely centimeters across. Our key technical insight is that both the mmWave radar and camera have complementary strengths. While the mmWave radar offers extremely high depth-resolution (centimeter-scale at even hundreds of meters) and through-occlusion imaging, its spatial resolution is extremely poor (several degrees). Our work explores mechanisms to achieve high resolution radar on a single combined platform, coupled with visual sensing and a variety of signal processing and learning strategies.

Approach

Through the project, we developed a novel framework that exploits multi-bounce scattering to enable mmWave sensing of objects that are not directly illuminated by the radar, and hence not are detected by conventional single-bounce methods. An example scenario is depicted below, where only the sofa is directly illuminated by the radar and hence is detected via single-bounce, but all other objects (dining furniture, trashcan and behind-radar human) are not detected. In the sequel, we refer to all objects not directly illuminated by the radar as *beyond field-of-view* objects, since they lie outside the radar's field-of-view (FoV), i.e., transmit beam. misses all other objects beyond the system's single-bounce field-of-view (FoV).

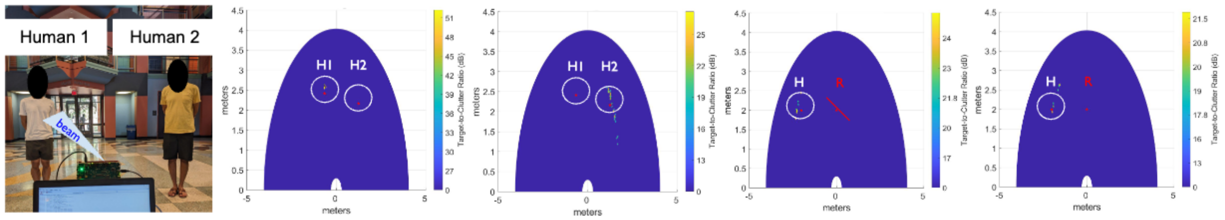


Methodology

As a key intermediate step towards solving the first challenge, we mathematically model diffuse multi-bounce scattering from objects. Our modeling insights lead to a matched filtering algorithm that directly localizes objects to their ground-truth locations along specific multi-bounce paths, without requiring any explicit ``ghost'' detection and remapping. To solve the second challenge, we propose to perform matched filtering and object detection separately & sequentially along single-, double- and triple-bounce. For each multi-bounce order, object detection is performed via a custom ordered statistics constant false alarm rate detector (OS-CFAR) and objects detected in lower multi-bounce orders are used as anchors to localize objects in undetected regions of the environment with higher-order multi-bounce. For example, in the context of the above Figure, the sofa is first localized via single-bounce, and subsequently treated as a source of further double-bounce to localize the dining furniture. The process is then extended to sense the behind-radar human and occluded trashcan via triple-bounce paths. We do not utilize fourth- and higher-order bounces since empirically we find the power of such paths too low to exploit.

Findings

We implement our system on a commercial digital mmWave multiple-input multiple-output (MIMO) radar testbed (TI AWR2243 cascade radar)and extensively evaluate its performance in five different indoor and outdoor scenarios, and exploit multi-bounce paths from a wide variety of everyday objects and surfaces, including human bodies, indoor furniture, and extended room and building features. We demonstrate that even with no prior knowledge of the environment, modeling and exploiting double-bounce and triple-bounce paths can improve the median localization error for human targets standing outside the radar's field-of-view by 2-10x over traditional single-bounce methods. The detailed results of our solution are to appear in ***ACM MobiCom 2024***, a major international conference.



(a) Setup in S1 (b) Single-bounce (c) Double-bounce (d) Whiteboard (S2) (e) Brick pillar (S4)

Conclusions

We present the design and evaluation of a framework that uses multi-bounce scattering to enable beyond-field-of-view sensing with a single mmWave radar without prior knowledge of the environment. Our implementation on a commercial MIMO radar demonstrated the possibility of localizing humans outside the transmit beam, behind-the-radar and around-corners, with 2-10x improvement in the median localization error in real-world scenarios even with no prior knowledge of the environment.

Recommendations developed from the project

We demonstrate through Hydra that even with no prior knowledge of the environment, modeling and exploiting double-bounce and triple-bounce paths can improve the median localization error for human targets standing outside a radar's field-of-view. The project work therefore demonstrates the value of a combination of radar signal processing, machine learning and hardware design to improve resolution and performance.

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