Privacy Leakage Study and Protection for Virtual Reality Devices

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WINLAB | Wireless Information Network Laboratory

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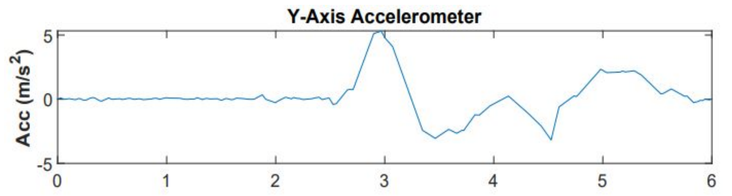
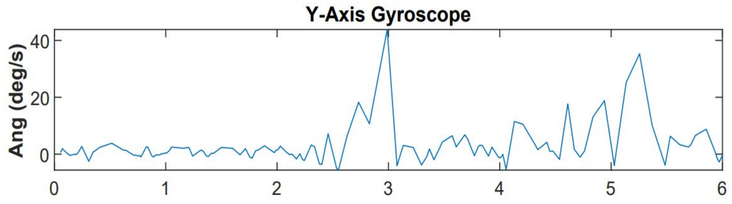
Motivation and Objectives

- Augmented Reality/Virtual Reality (AR/VR) technologies have been rapidly gaining popularity in recent years
- Motion sensor data encodes various types of the user's private information, such as activity information and preferences
- This project studies sensor data management in commercial AR/VR headsets and analyze the potential of private information leakage

Background

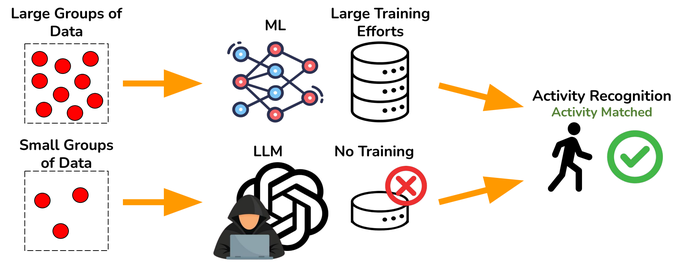
- User movements can be captured via built-in motion sensors (i.e., accelerometer and gyroscope) embedded in AR/VR headset and controllers
- Motion sensor recordings capture human motions in terms of linear acceleration and angles in a three-dimensional space





Decoding Privacy with AI

- Machine learning methods, such as Support Vector Machine (SVM), can learn to classify human activities by constructing support vectors to differentiate features of different classes
- Large Language Models (LLMs) have strong generalization capability in reasoning and inferring private activity information from motion sensor readings, without training efforts from the attacker

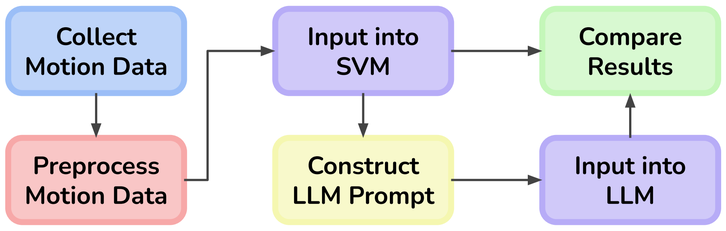


Methodology

- Utilizing SVM upon statistical features (e.g., mean, max, min, etc.) from motion sensor data to classify human activities
- Designing LLM prompts based on identified effective statistical features
  - Explaining the goal of the task and data types to be received
  - Expert knowledge about how to utilize the effective statistical features

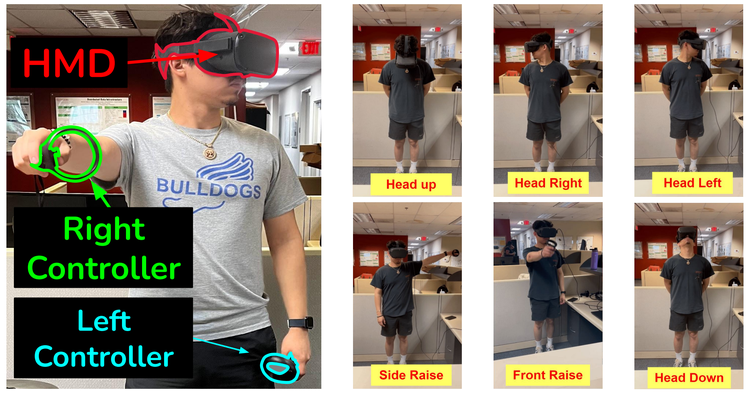
    1. **HMD Accelerometer**: Measures linear acceleration.
    Data: Time (s); x, y, and z-axis coordinates (m/s²).
    Interpretation: Acceleration values between -0.5 m/s² and 0.5 m/s² indicate the head is stable. Values below -0.5 m/s² and above 0.5 m/s² indicate head linear movement.
    2. **HMD Gyroscope**: Measures angular velocity.
    Data: Time (s); x, y, and z-axis coordinates (deg/s).
    Interpretation: Gyroscope values between -8 deg/s and 8 deg/s indicate the head is stable. Values below -8 deg/s and above 8 deg/s indicate head rotational movement.

  - Providing a response structure for results



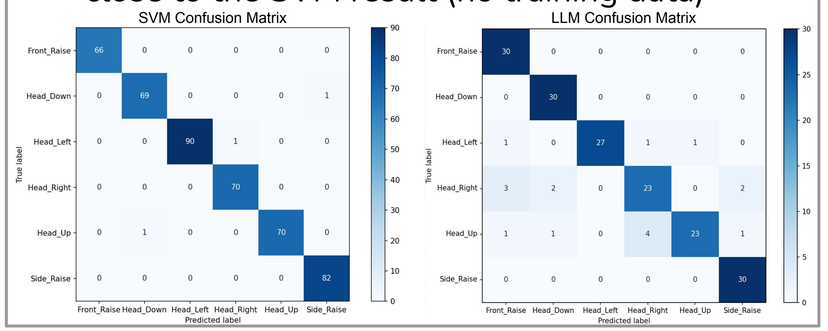
Experiment Setup

- Used Android Studio to develop an application to extract head-mounted display (HMD) and controller IMU data from Meta Quest
- Designed six motions (two head motions and four hand motions) for data collection
- Preprocessed and denoised data in MATLAB to create accurate waveforms and 3D graphs



Experiment Results

- Comparing accuracies between SVM and LLM
  - SVM test accuracy achieves 99.33%
  - LLM achieves an accuracy of 90.6% which is close to the SVM result (no training data)



Conclusion and Future Work

- We can achieve high activity inference accuracies with AI techniques (SVM and LLM)
- Our LLM test accuracy results could be improved with further fine-tuning the expert knowledge and the prompts for activity inference

References

[1] Xu, H., Han, L., Yang, Q., Li, M. and Srivastava, M., 2024, February. Penetrative AI: Making LLMs Comprehend the Physical World. In Proceedings of the 25th International Workshop on Mobile Computing Systems and Applications (pp. 1-7)
[2] Brownlee, J., 2018. 1D Convolutional Neural Network Models for Human Activity Recognition. Mach. Learn. Mastery, 26, p.2021.

Acknowledgement

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