Rolling Reality: Leveraging Rolling Shutter Effects in Photography for Privacy-Protected Human-Computer Interfaces

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Smart homes, medical devices, and education systems, among other emerging cyber-physical systems, offer immense potential for sensing-based user interfaces that utilize finger and hand gestures. However, current vision-based approaches face limitations such as time-consuming image processing, low 60 Hz location sampling rates, and privacy concerns associated with capturing hand frames. These methods are also inadequate for low-light environments and long detection ranges. Fortunately, advancements in computer technology and artificial intelligence (AI) have led to cost-effective and direct Human-Computer Interaction (HCI) through hand poses. This progress enables diverse applications, including controlling IoT devices in smart homes, enhancing user experiences in video games, and providing interactive operations in XR (AR, VR, and MR) mobile applications, thereby making interactions more intuitive and immersive.

Unlike traditional camera photography, which often relies on continuous, high-resolution image capture, our approach utilizes rolling shutter cameras integrated into ubiquitous IoT devices. These cameras provide higher-speed sampling essential for capturing fast-moving gestures with minimal latency. Additionally, rolling shutters automatically filter out sensitive scene information, such as text or people in the background, by focusing exclusively on the active light sources from the user's wearable LED-equipped gloves. This selective filtering enhances the accuracy and reliability of gesture detection by processing only relevant, user-specific data. To achieve precise finger tracking, we combine these rolling shutter cameras with LED-equipped gloves worn by users. The gloves emit controlled light patterns that facilitate three-dimensional finger positioning. The integration of LED lights with rolling shutter cameras enables clear definition of finger movements against diverse backgrounds and lighting conditions, ensuring accurate tracking of finger gestures.

Our approach also encompasses the development and implementation of sophisticated trajectory generation and optimization algorithms, meticulously designed to handle and process data captured from both LED-equipped gloves and rolling shutter cameras. These algorithms analyze the data in real-time to generate smooth and accurate three-dimensional representations of user finger movements. The trajectory generation component creates a continuous path based on detected finger positions, smoothing out irregularities to reflect natural finger movements. Optimization algorithms then refine these trajectories by correcting deviations and predicting future movements based on observed patterns, ensuring high precision. This integration enables the system to track and predict gestures with exceptional accuracy, even in dynamic and complex environments where movements may be rapid and erratic. The optimized trajectories enhance real-time responsiveness and allow the system to function effectively across various applications, from intricate hand gestures in interactive gaming to precise manipulations in augmented and virtual reality environments, making user interactions more intuitive and seamless while bridging the gap between physical gestures and digital responses.

The resulting system will be seamlessly integrated with AR/VR platforms to offer advanced human-computer interaction (HCI) capabilities within virtual spaces, enabling users to perform a wide range of interactive tasks with high accuracy, such as writing, drawing, and manipulating objects. This integration aims to create immersive and intuitive experiences in AR/VR environments, allowing users to engage with digital content in ways that closely replicate real-world interactions. Beyond these applications, the system holds significant potential for digital health, particularly in developing virtual input interfaces for individuals with conditions like Parkinson's disease. By providing a virtual environment where users can control and manipulate digital elements with enhanced accuracy, the system can help mitigate the impact of tremors and other motor symptoms. The precision of hand gesture tracking and the adaptability of the virtual interface can be tailored to offer supportive solutions, potentially improving the ease and effectiveness of interacting with digital tools for patients. Thus, the technology not only enriches user experiences in entertainment and interactive scenarios but also provides valuable benefits for enhancing quality of life in healthcare settings.