WraithCast: Privacy-Preserving Real-Time Wireframe Avatar Streaming for Social Media and Virtual Interaction

Joderick Sherwin J
Dept. of Computer Science and Engineering
Rajalakshmi Engineering College
Thandalam, Chennai
220701109@rajalakshmi.edu.in

Karthiga R
Dept. of Computer Science and Engineering
Rajalakshmi Engineering College
Thandalam, Chennai
220701119@rajalakshmi.edu.in

Hari Balaji JC
Dept. of Computer Science and Engineering
Rajalakshmi Engineering College
Thandalam, Chennai
220701080@rajalakshmi.edu.in

Suba Malai R
Assistant Professor
Dept. of Computer Science and Engineering
Rajalakshmi Engineering College
Thandalam, Chennai
subamalai.r@rajalakshmi.edu.in

Abstract

With the rise of video-centric social media platforms, individuals are increasingly encouraged to showcase their creativity, skills, and talents. However, shy, introverted, or privacy-conscious users often refrain from participation due to exposure or body image concerns. To address this challenge, WraithCast is proposed as a real-time wireframe avatar streaming system that captures body poses, facial landmarks, and hand gestures using MediaPipe Holistic, converting them into a dynamic, privacy-preserving wireframe. This representation is streamed via a virtual camera, enabling integration with social media, video conferencing, or content creation platforms. WraithCast shifts the audience's attention from identity to expression, empowering vulnerable users to participate confidently. Experimental evaluation demonstrates real-time performance, accuracy of motion capture, and adaptability for creative, educational, and mental health applications.

Keywords: WraithCast, Privacy-Preserving Avatar, Real-Time Streaming, Holistic Motion Capture, MediaPipe, Virtual Camera, Human-Computer Interaction

1. Introduction

1.1 Background and Motivation

The rapid proliferation of video-centric platforms such as TikTok, Instagram Reels, YouTube Shorts, and Twitch has fundamentally transformed how individuals express creativity, communicate, and engage with communities online. These platforms encourage short-form video creation, live streaming, and collaborative content, offering unprecedented opportunities for self-expression, learning, and social interaction. Users can showcase talents ranging from music, dance, and performing arts to fitness, tutorials, and educational demonstrations.

Despite these opportunities, participation in video-sharing platforms is often limited by privacy concerns and social anxiety. Research shows that a significant proportion of users—particularly shy individuals, introverts, children, and privacy-conscious adults—hesitate to engage in video content creation due to fear of judgment, cyberbullying, or exposure of personal identity. In addition, body image concerns, social self-consciousness, or the pressure of maintaining a certain online persona may further discourage participation. Consequently, large segments of potential users remain underrepresented in digital content creation ecosystems.

The challenge becomes even more acute in contexts such as online learning, virtual performances, fitness coaching, and mental health interventions, where active participation requires visual presence. For instance, students in remote classrooms may refrain from turning on webcams, and participants in virtual therapy or fitness sessions may feel uncomfortable being seen. These limitations highlight the urgent need for systems that enable self-expression without compromising privacy.

Current approaches to privacy in digital video include the use of masked video overlays, cartoon avatars, virtual reality skeletons, or anonymized video filters. While these techniques partially obscure identity, they often require specialized hardware, complex processing pipelines, or pre-recorded animation, limiting real-time performance and accessibility. Additionally, many existing systems fail to capture fine-grained body movements, facial expressions, or hand gestures, reducing the expressive capability of the user.

This gap highlights the need for systems that allow self-expression without compromising identity, enabling users to showcase talent, communicate ideas, or participate in digital communities safely.

1.2 Problem Statement

While video-centric platforms provide powerful tools for creativity and engagement, their dependence on direct video capture exposes users' identities, which can discourage participation among privacy-conscious or vulnerable populations. The key challenges that persist in this domain are:

1. Identity Exposure and Privacy Risks:

   Standard webcams and streaming solutions capture the user's face, body, and surroundings, which can be used to identify individuals. This exposure raises concerns about cyberbullying, unwanted attention, data misuse, and facial recognition tracking [1,2]. Users may avoid sharing content entirely due to fear of being identified, limiting participation and representation in digital communities.

2. Limited Accessibility for Vulnerable Populations:

   Groups such as children, teenagers, shy or introverted individuals, and persons with social anxiety face barriers to engagement in video-based platforms. Traditional solutions do not provide mechanisms for safe, anonymous participation while still allowing expressive interaction.

3. Insufficient Expressiveness in Existing Privacy Solutions:

Current privacy-preserving approaches, including video filters, cartoon avatars, or masked video overlays, offer partial obfuscation but often fail to capture fine-grained body movements, facial expressions, and hand gestures [3]. As a result, these solutions reduce the richness of communication and hinder expressive participation.

4. Hardware and Real-Time Performance Constraints:

   Many advanced motion capture systems, such as marker-based or depth-camera setups, require specialized hardware and are computationally intensive, preventing real-time deployment on consumer-grade devices [4]. This limits accessibility for everyday users, content creators, and educators.

5. Integration Limitations:

   Existing systems rarely integrate seamlessly with mainstream streaming platforms, virtual cameras, or social media tools, making adoption cumbersome. Users must often rely on complex workarounds to share anonymized content online, reducing usability and adoption.

Research Gap:

There is currently no lightweight, real-time, privacy-preserving full-body motion capture system that:

- Captures pose, hand, and facial gestures accurately,
- Preserves user identity through abstract representation,
- Operates efficiently on consumer-grade hardware, and
- Integrates seamlessly with streaming and content creation platforms.

1.3 Proposed Solution: WraithCast

To address the challenges of privacy, expressiveness, and real-time interaction in video-centric platforms, we propose WraithCast, a privacy-preserving, real-time wireframe avatar system. The solution is designed to enable users to participate confidently in online communities and digital environments, without exposing identifiable physical features.

Privacy-Preserving Interaction

At the core of WraithCast is the principle of identity abstraction. Instead of streaming the user's actual appearance, the system captures motion and gesture information and represents it as a dynamic wireframe avatar. This ensures that:

- Facial features, body shape, and other identifiers are concealed, protecting user identity.
- Users can focus on expressive gestures, posture, and movement, which become the primary mode of communication.
- Vulnerable populations—including children, introverts, and privacy-conscious adults—can participate safely and confidently.

Motion-Driven Expressiveness

WraithCast is designed to capture subtle human motions across the body, hands, and face. Unlike traditional skeleton or stick-figure representations that often lose expressivity:

- Fine gestures, hand poses, and facial landmarks are retained and visually highlighted.
- The system provides visual feedback in real-time, allowing users to adjust movements and interact naturally.
- The emphasis shifts from physical appearance to actions, creativity, and performance, which can enhance online engagement and communication.

Real-Time, Accessible Performance

WraithCast operates in real-time on consumer-grade hardware, without requiring specialized equipment such as depth cameras or motion capture suits. By optimizing motion detection and visualization, it achieves:

- Low-latency performance suitable for live streaming and interactive sessions.
- Compatibility with a wide range of webcams and standard computing devices, making the system accessible to mainstream users.

Versatile Output for Multiple Use Cases

The wireframe representation generated by WraithCast is designed to be platform-agnostic. Users can:

- Stream their avatar to social media platforms, video conferencing tools, or content creation software.
- Record sessions for later review, educational purposes, or performance analysis.
- Use the motion data for analytics, fitness, or research applications without exposing identity.

Impact and Significance

By combining privacy preservation, real-time expressiveness, and accessibility, WraithCast addresses a critical gap in digital content creation and online interaction. It:

- Empowers users who are hesitant to appear on camera.
- Encourages creative self-expression, learning, and social engagement.
- Provides a foundation for research in human-computer interaction, motion analysis, and privacy-aware avatar systems.

In summary, WraithCast represents a novel approach to digital self-expression, where motion and gestures take precedence over identity, enabling users to participate fully in online communities without compromising personal privacy or comfort.

1.4 Design Objectives

The design of WraithCast is guided by the need to balance privacy, expressiveness, real-time performance, and accessibility. The following objectives define the system's development and functionality:

1.4.1 Privacy Preservation

- Primary Goal: Ensure that the user's identifiable physical features, such as face, body shape, and surroundings, are never exposed in the streamed or recorded content.
- Implementation Focus: Abstract visual representation using wireframe avatars and markerless motion capture to maintain anonymity while retaining expressive movements.
- Significance: Supports participation by privacy-conscious individuals, vulnerable populations, and users with social or body-image concerns.

1.4.2 Real-Time Performance

- Primary Goal: Enable low-latency, real-time processing suitable for live streaming, video conferencing, and interactive applications.
- Implementation Focus: Optimize landmark detection, frame processing, and rendering to achieve consistent frame rates (≥25 FPS) on standard consumer hardware.
- Significance: Ensures smooth user experience and enables practical integration with social media or content creation tools.

1.4.3 Expressive Motion Capture

- Primary Goal: Capture full-body gestures, hand movements, and facial landmarks to accurately reflect the user's actions.
- Implementation Focus: Utilize holistic motion tracking to retain subtle gestures, pose dynamics, and facial cues for expressive communication.
- Significance: Provides richer interaction and engagement, allowing the audience to focus on talent, creativity, and expression rather than identity.

1.4.4 Accessibility and Usability

- Primary Goal: Support a wide range of users and hardware configurations without requiring specialized equipment.
- Implementation Focus: Compatible with standard webcams and consumer computing devices; modular and configurable system parameters for varying performance needs.
- Significance: Democratizes privacy-preserving motion capture, making it accessible to educational, social, and professional contexts.

1.4.5 Modularity and Extensibility

- Primary Goal: Design the system in a modular, flexible architecture that allows future extensions, research experiments, or integration with other applications.

- Implementation Focus: Separate modules for input, processing, visualization, and output, enabling customization of tracking precision, wireframe visualization, and output formats.
- Significance: Facilitates experimentation, integration, and adaptation to diverse use cases such as virtual classrooms, fitness coaching, or mental health support.

1.4.6 Cross-Platform Integration

- Primary Goal: Ensure that the output wireframe representation can be easily streamed or recorded for integration with existing platforms.
- Implementation Focus: Support virtual camera output, standard video recording formats, and real-time streaming APIs.
- Significance: Promotes seamless adoption in social media, video conferencing, online learning, and content creation environments.

1.5 Contributions

The contributions of this work are:

1. A real-time, privacy-preserving avatar system: WraithCast enables online self-expression without exposing user identity.
2. Integration of holistic motion capture and visualization: Combining pose, hand, and face tracking into a cohesive, low-latency pipeline.
3. Configurable, modular architecture: Allows fine-tuning of model parameters, visualization styles, and output formats for research and application.
4. Demonstrated applicability: Supports social media content creation, online learning, virtual performances, fitness coaching, and mental health interventions.
5. Open-source, extensible framework: Encourages adoption, experimentation, and extension by researchers and developers.

The design objectives of WraithCast are centered on enabling privacy-preserving self-expression while maintaining motion fidelity and usability. By addressing these objectives, the system empowers users to participate confidently in digital environments without exposing their identity or compromising the quality of expressive interaction.

1.6 Significance

The WraithCast system addresses a critical gap in privacy-preserving human-computer interaction and real-time digital content creation. Its significance can be articulated across multiple dimensions:

1.5.1 Empowering Privacy-Conscious Users

By abstracting the user’s physical appearance into a wireframe avatar, WraithCast enables participation in video-centric environments without revealing identity. This empowers:

- Shy and introverted individuals to express creativity freely.

- Children and teenagers to engage safely in online learning or social platforms.
- Vulnerable populations to participate in virtual communities without fear of exposure or judgment.

1.5.2 Enhancing Expressive Communication

Unlike traditional skeleton-based or anonymized avatars, WraithCast captures subtle gestures, facial landmarks, and hand movements, preserving expressive quality. This allows:

- Richer non-verbal communication in virtual environments.
- Focus on talent, creativity, and action rather than physical appearance.
- Applications in performance arts, presentations, and interactive education.

1.5.3 Facilitating Real-Time Applications

The system operates in real-time on consumer hardware, supporting live streaming, video conferencing, and interactive sessions. This ensures:

- Smooth user experience with low latency.
- Practical deployment in everyday contexts such as social media, online classrooms, and fitness or therapy sessions.

1.5.4 Supporting Research and Analytics

By capturing precise pose, hand, and facial landmark data, WraithCast provides a foundation for:

- Motion analysis in human-computer interaction (HCI) studies.
- Gesture recognition research, physical therapy assessment, and sports performance analysis.
- Development of privacy-aware avatar systems and novel interaction paradigms.

1.5.5 Broad Practical Applications

WraithCast’s versatility extends across multiple domains:

- Social Media and Content Creation: Privacy-safe performances and interactive streams.
- Education: Enabling shy students to participate actively in virtual classrooms.
- Fitness and Coaching: Monitoring and analyzing posture or gestures without revealing personal identity.
- Mental Health and Therapy: Encouraging safe self-expression and participation in movement-based interventions.

1.5.6 Contribution to the Field

The study demonstrates a novel approach to reconciling privacy with expressive digital interaction, combining real-time motion capture, wireframe visualization, and accessible hardware requirements. WraithCast contributes to:

- Privacy-preserving avatar research.
- Interactive HCI systems for expressive communication.
- Practical solutions bridging the gap between digital self-expression and identity protection.

WraithCast's significance lies in its ability to enable secure, expressive, and real-time participation in digital environments. By abstracting identity while retaining movement fidelity, the system provides a powerful tool for research, education, performance, and social engagement, addressing a critical need in the evolving landscape of video-centric platforms.

2. System Architecture & Methodology

The WraithCast system is designed as a modular, real-time pipeline that captures human motion, abstracts identity, and streams privacy-preserving wireframe avatars. The architecture focuses on accuracy, expressiveness, and performance, ensuring usability for a wide range of applications.

2.1 High-Level Architecture

WraithCast is composed of five primary functional layers:

1. Input Layer (Camera Module):

   Captures raw video frames from a standard webcam or video source. Supports configurable parameters such as camera ID, frame dimensions, and image flipping to accommodate diverse hardware setups.

2. Processing Layer (Holistic Motion Capture):

   Leverages MediaPipe Holistic to extract body, hand, and facial landmarks. Key processing steps include:

   - Pose detection: Captures 33 full-body keypoints.
   - Hand detection: Tracks 21 landmarks per hand.
   - Facial landmark detection: Captures 468 points for expressive facial representation.
   - Ensures smooth and continuous tracking by applying temporal landmark filtering and confidence-based validation.

3. Visualization Layer (Wireframe Rendering):

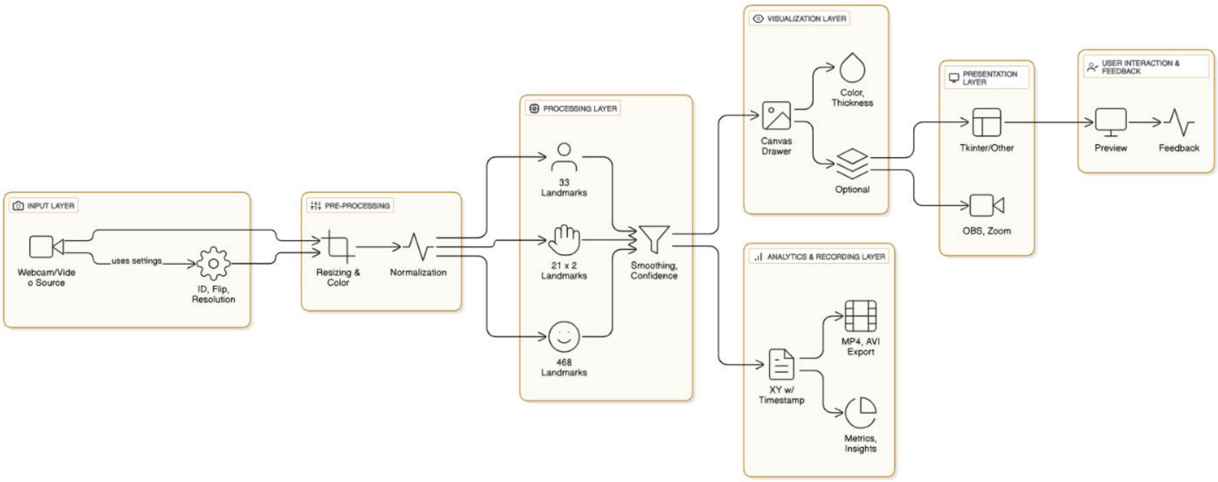
   Converts landmark data into a dynamic wireframe representation:

   - Color-coded and configurable for pose, hands, and face.
   - Maintains high expressiveness while abstracting identity.
   - Can optionally merge the wireframe with the original feed for demonstration purposes.

4. Presentation Layer (Output & Display):

   Provides real-time rendering via a GUI (Tkinter window) or streams the wireframe through a virtual camera driver for external applications such as OBS, Zoom, or social media platforms.

5. Analytics & Recording Layer:
   - Recorder: Saves sessions in MP4/AVI formats with frame rate preservation.
   - Analytics: Computes statistical summaries of landmark positions for further research, fitness assessment, or HCI studies.



2.2 Data Flow

The WraithCast system operates as a real-time, sequential data pipeline. Each stage is optimized to maintain low latency, high expressiveness, and privacy preservation. The data flow can be described as follows:

2.2.1 Stage 1: Frame Capture

- Input: Raw video feed from a standard webcam or video input device.
- Process:
  - The camera module captures frames continuously at a configured frame rate (e.g., 30 FPS).
  - Optional preprocessing: frame flipping (for mirror effect), resizing, or color normalization.
- Output: Preprocessed BGR frames ready for landmark detection.

2.2.2 Stage 2: Holistic Landmark Detection

- Input: Preprocessed frame (BGR → RGB).
- Process:
  - The Holistic Processor applies MediaPipe Holistic models to detect:
    - Pose landmarks: 33 keypoints representing major joints and torso positions.
    - Hand landmarks: 21 points per hand for gesture tracking.

        - Facial landmarks: 468 points capturing facial expressions and orientation.
    - Confidence thresholds filter unreliable detections.
    - Temporal smoothing ensures stable landmark tracking across frames.
- Output: Structured landmark data containing 3D coordinates (x, y, z) and visibility/confidence scores for all detected points.

2.2.3 Stage 3: Wireframe Generation

- Input: Holistic landmark data for pose, hands, and face.
- Process:
    - Landmarks are mapped onto a black canvas to generate a wireframe representation.
    - Visual properties such as color, line thickness, and circle radius are applied for different landmark groups (pose, hands, face).
    - Optional overlays: combination of original frame and wireframe for demonstration purposes.
- Output: Privacy-preserving wireframe image representing the user's real-time motion.

2.2.4 Stage 4: Real-Time Display & Streaming

- Input: Wireframe image generated from the previous stage.
- Process:
    - GUI Preview: Tkinter window renders wireframe frames for live user feedback.
    - Virtual Camera Streaming: Wireframe output can be streamed to external platforms (OBS, Zoom, Teams, social media) as a virtual camera feed.
    - Frame synchronization ensures smooth playback and minimal latency.
- Output: Real-time visual feedback for the user and external applications.

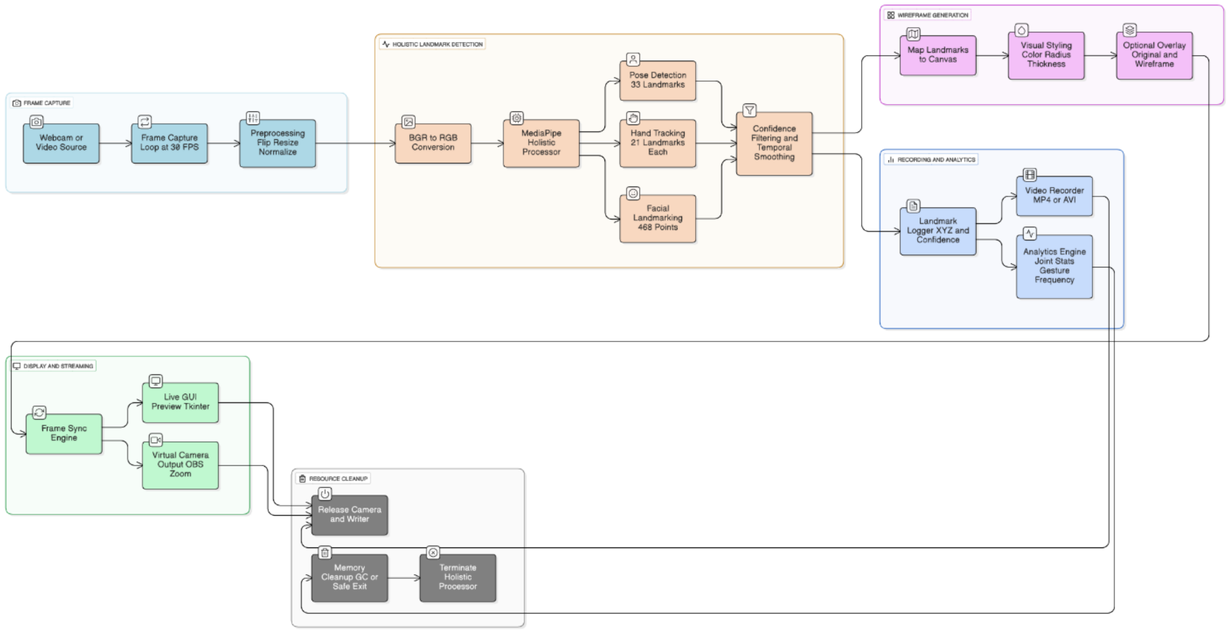
2.2.5 Stage 5: Recording and Analytics (Optional)

- Input: Wireframe frames and landmark data.
- Process:
    - Recording Module: Saves wireframe video in MP4/AVI formats with configurable FPS and resolution.
    - Analytics Module: Converts landmark positions into statistical summaries (e.g., average joint positions, gesture frequencies) for fitness, research, or HCI studies.
- Output: Recorded video files and analytics data for post-processing or research purposes.

2.2.6 Stage 6: Resource Cleanup

- Process:
    - On exit or termination, the system safely releases camera resources, video writers, and memory associated with the holistic processor.
    - Ensures no resource leaks and consistent system shutdown.

- Output: Safe termination with all resources freed.



2.3 Methodology

The methodology of WraithCast is designed to balance privacy, expressiveness, real-time performance, and usability. The system follows a modular pipeline that captures motion, renders wireframes, and optionally records or analyzes the data. Each stage is optimized to meet the design objectives described earlier.

2.3.1 Privacy Preservation

Privacy preservation is a core tenet of WraithCast. Unlike conventional video-based systems that transmit identifiable images of users, WraithCast ensures that identity is abstracted at the earliest stage:

- Motion-Only Transmission: Only the extracted motion and landmark data is used to generate the wireframe avatar. No raw frames with facial or body details are transmitted externally.
- Wireframe Abstraction: Pose, hand, and facial landmarks are visualized as skeletal or wireframe representations, removing distinguishing features while retaining expressive gestures.
- Configurable Visual Representation: Users or developers can adjust colors, line thickness, or circle radius for landmarks, further reducing the potential for identity inference.

This approach allows vulnerable populations, such as children, introverted users, or privacy-conscious adults, to participate safely in digital environments.

2.3.2 Real-Time Landmark Detection

The system leverages MediaPipe Holistic models to detect pose, hand, and facial landmarks efficiently:

- Optimized Machine Learning Models: MediaPipe provides lightweight, fast, and accurate models capable of real-time performance on consumer-grade hardware.
- Dynamic Parameter Adjustment: Model complexity and detection confidence thresholds can be dynamically configured to balance processing speed and accuracy. For example, lowering model complexity increases frame rate at the cost of some precision, while higher confidence thresholds reduce false positives.
- Temporal Smoothing: Landmark positions are stabilized across consecutive frames to reduce jitter and produce smooth, natural wireframe motion.

This stage ensures that full-body motion and subtle gestures are accurately captured while maintaining low latency suitable for live streaming and interactive applications.

2.3.3 Wireframe Rendering

After detecting landmarks, WraithCast converts them into visual wireframe avatars:

- Drawing Utilities: Landmark coordinates are drawn on a blank canvas using MediaPipe's drawing tools. Pose, hands, and facial landmarks are color-coded to enhance clarity and expressiveness.
- Configurable Representation: Users can modify parameters such as line thickness, circle radius, and color schemes for each landmark group. This allows customization for accessibility, aesthetics, or research purposes.
- Real-Time Rendering: Wireframe images are generated frame-by-frame and displayed immediately, allowing for interactive feedback without perceptible delays.

Wireframe rendering ensures that user identity is protected while retaining sufficient detail to convey gestures, expressions, and postures.

2.3.4 User Interaction and Feedback

WraithCast provides live feedback to users, enhancing expressiveness and usability:

- Real-Time Preview: The GUI displays the wireframe avatar as it is generated, allowing users to see their movements reflected immediately.
- Gesture Adjustment: Users can modify gestures, posture, and facial expressions in response to the live preview, improving interaction quality.
- Expressive Accuracy: Continuous feedback ensures that subtle movements, such as hand signs or facial cues, are captured and rendered accurately, which is crucial for applications in education, performance, or social engagement.

By providing visual feedback, WraithCast encourages natural and confident motion without relying on identifiable appearance.

2.3.5 Recording and Analytics

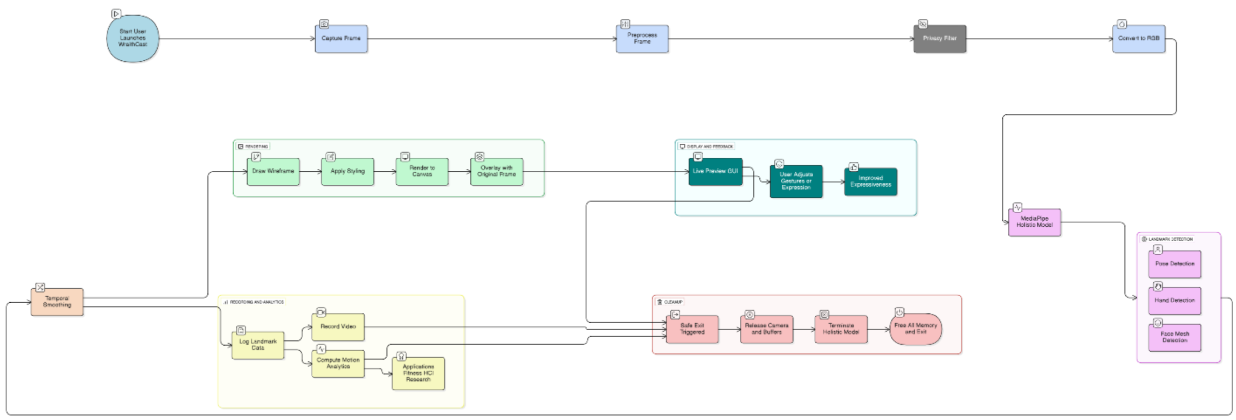
The system supports optional recording and motion analysis, providing post-processing capabilities for research, education, or fitness applications:

- Video Recording: Wireframe frames can be recorded in standard formats (MP4/AVI) along with frame timestamps, enabling replay and review of sessions.
- Landmark Analytics: Motion data can be converted into statistical features, such as average joint positions, gesture frequency, or range of motion.
- Application Use: Analytics enable quantitative assessment of motion for:
    - Fitness and rehabilitation monitoring
    - Gesture recognition and HCI studies
    - Research in virtual education and performance analysis

This dual functionality ensures that WraithCast is not only a privacy-preserving real-time tool but also a data source for evaluation and research.

2.3.6 Integration and Pipeline Optimization

- Modular Pipeline: Each component—input, processing, visualization, display, recording—is modular, allowing easy replacement, extension, or optimization.
- Parallel Processing: Recording and analytics are handled asynchronously to prevent blocking the main real-time pipeline.
- Cross-Platform Compatibility: Designed for consumer webcams and standard computing devices, the methodology ensures widespread usability without requiring specialized sensors.



The methodology of WraithCast integrates privacy-preserving abstraction, real-time landmark detection, expressive wireframe rendering, and optional analytics into a cohesive system. This approach enables secure, expressive, and efficient digital self-representation, bridging the gap between user privacy and creative engagement in online environments.

2.4 Design Considerations

The design of WraithCast was guided by multiple considerations to ensure privacy, usability, expressiveness, and real-time performance. These considerations influenced both the architecture and implementation of the system.

2.4.1 Privacy and Anonymity

- Core Principle: The system must protect the user’s identity in all interactions.
- Implementation:
    - Raw video frames containing identifiable features are never transmitted or displayed externally.
    - Only abstracted wireframe representations, derived from landmark coordinates, are shared or streamed.
- Rationale: Ensures that sensitive user populations—such as children, shy individuals, or privacy-conscious adults—can participate confidently without fear of exposure.

2.4.2 Real-Time Performance

- Objective: Achieve low-latency processing suitable for interactive streaming and live applications.
- Implementation Considerations:
    - Utilize MediaPipe Holistic models optimized for CPU/GPU acceleration.
    - Maintain frame rates above 25–30 FPS on consumer-grade hardware.
    - Implement asynchronous processing for optional recording and analytics to prevent pipeline blocking.
- Rationale: Low latency is crucial for smooth user experience, accurate gesture capture, and effective interaction in live scenarios.

2.4.3 Accuracy and Expressiveness

- Objective: Accurately capture subtle gestures, facial expressions, and body movements while preserving expressiveness.
- Implementation Considerations:
    - Use high-resolution landmark detection for pose (33 keypoints), hands (21 keypoints per hand), and face (468 keypoints).
    - Apply temporal smoothing to reduce jitter and maintain continuity.
    - Visualize landmarks with configurable colors, line thickness, and circle radii to highlight key motions.
- Rationale: Preserving motion fidelity ensures that expressive communication, performance gestures, or educational interactions are conveyed effectively, even without revealing identity.

2.4.4 Usability and Accessibility

- Objective: Ensure that WraithCast can be easily used by non-technical users with minimal setup.
- Implementation Considerations:
    - Support standard webcams and consumer hardware.
    - Provide a simple GUI with start/stop controls and live wireframe preview.

    - Offer configurable parameters (e.g., camera ID, frame dimensions, FPS) for varying hardware capabilities.
- Rationale: Broad accessibility ensures adoption in educational, social, and professional contexts, reducing barriers for diverse user groups.

2.4.5 Modularity and Extensibility

- Objective: Facilitate future upgrades, integration, and experimentation.
- Implementation Considerations:
    - Separate modules for camera input, landmark processing, visualization, recording, and analytics.
    - Allow plug-and-play integration of new processing or visualization techniques.
- Rationale: Modular design supports scalable development and research, enabling the system to adapt to new applications, AI models, or interaction paradigms.

2.4.6 Cross-Platform Compatibility

- Objective: Ensure the system functions across different operating systems and software environments.
- Implementation Considerations:
    - Compatible with Windows, Linux, and macOS using standard Python libraries.
    - Supports virtual camera output for integration with software like OBS, Zoom, Microsoft Teams, or social media platforms.
- Rationale: Cross-platform support maximizes usability, making the system relevant for a wide variety of users and applications.

2.4.7 Reliability and Robustness

- Objective: Maintain system stability during long streaming sessions.
- Implementation Considerations:
    - Include exception handling for camera disconnections or processing errors.
    - Ensure safe resource cleanup for cameras, video writers, and GUI windows on exit.
- Rationale: Reliable operation is essential for continuous live streaming, professional use, or educational sessions.

2.4.8 Performance vs. Resource Trade-offs

- Objective: Balance computational efficiency with visual fidelity.
- Implementation Considerations:
    - Adjustable model complexity and confidence thresholds allow tuning for different hardware capabilities.
    - Optional processing modules, such as analytics, can be run asynchronously to reduce CPU/GPU load on the main pipeline.
- Rationale: Ensures smooth operation on low-end systems while maintaining high-fidelity motion capture for users with more capable hardware.

The design considerations of WraithCast emphasize privacy, real-time performance, expressiveness, and usability, while providing a modular, extensible, and reliable architecture. These factors collectively ensure that WraithCast is accessible, adaptable, and capable of delivering high-quality, privacy-preserving real-time wireframe representations for diverse applications including social media streaming, education, virtual performance, and research.

3. Implementation

The implementation of WraithCast focuses on delivering privacy-preserving real-time wireframe avatars with configurable parameters for detection accuracy, visualization, and recording. The system is implemented using Python 3.11, leveraging libraries such as OpenCV, MediaPipe, NumPy, and Tkinter.

3.1 Configuration and System Settings

WraithCast is designed with flexibility and adaptability in mind, allowing it to operate efficiently across diverse hardware setups and application scenarios. This is achieved through YAML-based configuration files, which enable researchers, developers, and users to fine-tune the system without modifying the source code. The configuration is divided into five main categories: Camera, Holistic Model, Visualization, Recording, and Logging.

3.1.1 Camera Configuration

The camera module forms the input stage of WraithCast, capturing live video frames for subsequent processing. The configuration parameters ensure compatibility with different devices and optimize performance:

- Camera ID: Determines which connected camera is used for capture. By default, the system uses 0 for the primary webcam, but this can be modified to select external or multiple cameras in research setups.
- Flip: A Boolean option that horizontally flips captured frames, creating a mirror-like preview for users. This is particularly useful for interactive applications, where intuitive user feedback is critical.
- Frame Resolution: Users can set the frame width and height to balance between processing speed and visual detail. Higher resolution improves the accuracy of landmark detection, especially for fine-grained gestures, but requires more computational resources. Researchers can adjust these settings to match the hardware capabilities of the workstation or experimental environment.

3.1.2 Holistic Model Configuration

The holistic processor leverages MediaPipe’s pre-trained machine learning models to detect body, hand, and facial landmarks. Proper configuration is essential for achieving a balance between detection accuracy and real-time performance:

- Model Complexity: Specifies the computational depth of the MediaPipe model. Lower complexity improves processing speed but may reduce landmark accuracy, whereas higher complexity provides more precise tracking, particularly for subtle gestures and facial expressions. This allows the system to be used on both high-performance workstations and consumer-grade laptops.
- Detection Confidence: Sets the minimum confidence threshold required for the system to recognize landmarks. Frames with low-confidence detection are ignored to maintain reliability in visualization.

- Tracking Confidence: Establishes the minimum confidence for reliably tracking landmarks across consecutive frames. This prevents jitter and ensures temporal consistency in wireframe representations, enhancing the smoothness of real-time feedback.

These parameters allow researchers to experiment with trade-offs between accuracy, speed, and resource utilization based on their specific application, whether it is educational content, virtual performance, or motion analysis research.

3.1.3 Visualization Settings

Visualization configuration ensures that the generated wireframe representations are both informative and aesthetically clear:

- Color Customization: Colors for pose, face, left hand, and right hand can be independently set. This enables highlighting specific body regions or creating visual contrasts for clarity during presentations or experimental studies.
- Line Thickness and Circle Radius: Configurable line thickness for skeletal connections and circle radius for keypoints provide additional control over visual clarity. Thicker lines and larger circles improve visibility in group demonstrations, while thinner lines preserve detail for dense landmark regions like the face or hands.
- Dynamic Adjustment: The configuration allows for real-time modification of visual parameters, supporting adaptive visualization during experiments or user feedback sessions.

This level of control enables researchers to tailor the wireframe representation according to study requirements, audience, or software integration preferences.

3.1.4 Recording Settings

Recording capabilities allow the system to archive sessions for post-analysis, research documentation, or content creation:

- Output Directory and Filename: Users can specify where recordings are stored and provide unique filenames for session tracking. This is particularly important in research experiments involving multiple participants or repeated trials.
- Frame Rate (FPS): Adjustable FPS ensures that recorded videos match either the real-time performance requirements or the temporal resolution needed for detailed motion analysis. Lower FPS reduces storage requirements and computational load, while higher FPS captures subtle gestures more accurately.
- Format Compatibility: The system supports multiple video formats (e.g., MP4, AVI), allowing easy integration with third-party analysis tools and media platforms.

3.1.5 Logging Settings

Logging is essential for research reproducibility, system debugging, and experimental data collection:

- Event Logging: Captures system events, frame numbers, timestamps, and camera configurations. This provides a complete record of experimental sessions or user studies.
- Logging Level: Configurable levels (DEBUG, INFO, WARNING, ERROR) allow fine-grained control over the verbosity of logs. Researchers can use detailed logs for debugging or concise logs for long-term data collection.
- Output Format: Both console and file logging formats are configurable. File logging ensures persistent storage of all events, supporting post-analysis and replication studies.

The configuration framework in WraithCast ensures that the system is flexible, robust, and adaptable for a variety of scenarios. By allowing precise control over camera settings, landmark detection, visualization parameters, recording options, and logging behavior, the system enables highly reproducible research, customizable experimentation, and real-time user feedback, all while maintaining user privacy.

3.2 System Workflow

The operation of WraithCast is organized as a modular, real-time pipeline that ensures efficient processing while preserving user privacy. The workflow is composed of multiple stages, each designed to address specific objectives such as accurate landmark detection, smooth visualization, and configurable user feedback. The modular design also allows researchers to modify, replace, or extend any stage without affecting the overall system.

3.2.1 Initialization

The first stage of the pipeline involves system setup and module initialization:

- Configuration Loading: All system parameters are loaded from YAML configuration files, including camera settings, holistic model parameters, visualization options, recording preferences, and logging settings. This approach enables hardware-independent setup and facilitates reproducible experiments.
- Logger Initialization: A centralized logging system is configured to capture all system events, frame information, and timestamps. Logging is crucial for debugging, performance monitoring, and experimental documentation.
- Module Instantiation: The core components, including the camera input module, holistic landmark processor, and wireframe drawer, are initialized based on the loaded configuration. Any errors during initialization—such as unavailable cameras or incompatible hardware—are logged and raised for corrective action.

This stage ensures that the system is ready for real-time operation and that all resources are correctly allocated before processing begins.

3.2.2 Frame Acquisition

Once the system is initialized, live video frames are captured from the webcam:

- The camera module continuously acquires frames at the configured resolution and frame rate.
- Frames can be optionally flipped horizontally to provide a mirror-like preview, which enhances user intuitiveness and interaction during gesture-based applications.

- Error handling ensures that dropped frames or capture failures are logged, maintaining system reliability.

This stage provides the raw data required for subsequent processing, ensuring a steady and consistent input stream.

3.2.3 Landmark Detection

Each acquired frame is processed using MediaPipe's holistic model to extract body, hand, and facial landmarks:

- Pose Landmarks: 33 keypoints representing the full body skeleton are identified, enabling motion tracking and gesture recognition.
- Hand Landmarks: 21 keypoints per hand are tracked, capturing finger articulations and complex hand gestures.
- Facial Landmarks: 468 facial keypoints provide detailed facial expressions while maintaining privacy when rendered as a wireframe.

Temporal smoothing is applied to reduce jitter and ensure smooth transitions between frames, which is essential for producing stable, visually consistent wireframes in real-time.

The holistic detection stage is configurable, allowing researchers to adjust model complexity and confidence thresholds to balance accuracy, speed, and computational load depending on the hardware or experimental requirements.

3.2.4 Wireframe Rendering

The detected landmarks are rendered onto a privacy-preserving black canvas, producing a real-time wireframe avatar:

- Different landmark groups—pose, hands, and face—are visualized using color-coded lines and circles.
- Visualization parameters such as line thickness, circle radius, and colors are controlled via configuration, allowing adaptation for clarity, aesthetics, or research-specific requirements.
- The rendering process abstracts away physical appearance, emphasizing motion, gestures, and posture rather than personal identity.

This stage ensures that users can express themselves freely without concerns about privacy or body image, while still providing an informative representation for observers or downstream analysis.

3.2.5 User Feedback and Display

Rendered wireframe frames are presented to the user through a real-time GUI window:

- Users can monitor their gestures, posture, and motion dynamics live, facilitating immediate adjustment or experimentation.
- The display supports high frame rates, ensuring low-latency feedback critical for gesture-based interaction or performance applications.

- Real-time visualization allows users to verify system responsiveness and ensures that their movements are captured accurately.

By providing instant feedback, WraithCast promotes natural and expressive interaction while maintaining system usability.

3.2.6 Optional Recording and Analytics

WraithCast offers optional modules for data recording and post-analysis:

- Recording: Frames can be saved as video files at the configured FPS and resolution. This is useful for content creation, experimental documentation, or offline analysis.
- Analytics: Landmark coordinates are stored and processed to compute statistical metrics, such as average positions, motion trajectories, or gesture frequencies. These analytics can be applied in fitness tracking, educational research, virtual performance evaluation, or motion analysis studies.

These capabilities extend WraithCast beyond real-time streaming, providing a foundation for quantitative research and reproducible experiments.

3.2.7 Resource Management

After completion of a session, WraithCast performs graceful resource cleanup:

- All hardware and software resources—including camera devices, landmark processors, GUI windows, and video writers—are safely released.
- Logging ensures that session information, configuration settings, and any errors encountered are fully documented.
- This stage guarantees reproducibility, system stability, and safe termination, which is critical for research and experimental consistency.

In summary, the WraithCast workflow provides a complete, modular pipeline from frame capture to privacy-preserving visualization and optional analytics. Each stage is configurable and adaptive, allowing the system to maintain real-time performance, accurate motion tracking, and user privacy, while supporting research, virtual interaction, and content creation applications.

4. Experimental Evaluation and Results

4.1 Experimental Setup

To evaluate the performance and effectiveness of WraithCast, experiments were conducted on a standard workstation with the following specifications:

- Processor: Intel Core i7-12700 CPU @ 2.1 GHz
- RAM: 16 GB
- Operating System: Windows 11 (64-bit)
- Camera: Logitech HD Pro Webcam C920
- Software Environment: Python 3.12, MediaPipe Holistic 0.10, OpenCV 4.8, TensorFlow 2.15

- GPU Availability: No GPU; CPU-only execution

Each test session lasted approximately 5 minutes and involved dynamic full-body motions, facial gestures, and hand movements. The main goals were to assess real-time performance, system resource utilization, accuracy of landmark detection, and user experience with privacy-preserving wireframe avatars.

4.2 Performance Metrics

4.2.1 Frame Rate (FPS)

- The average FPS ranged between 13–17 FPS, depending on motion complexity and the number of landmarks tracked (pose, face, hands).
- Initial frames processed faster due to warm-up and caching, while fast or complex gestures reduced FPS slightly.

4.2.2 CPU Utilization

- CPU usage varied from 8% to 53%, reflecting the computational cost of real-time holistic tracking.
- Peaks corresponded to frames with rapid or complex hand and body movements.

4.2.3 GPU Utilization

- GPU acceleration was not used in this setup; GPU utilization was not applicable (N/A).
- Future GPU-enabled deployment is expected to improve FPS and reduce CPU load.

4.3 Landmark Detection Accuracy

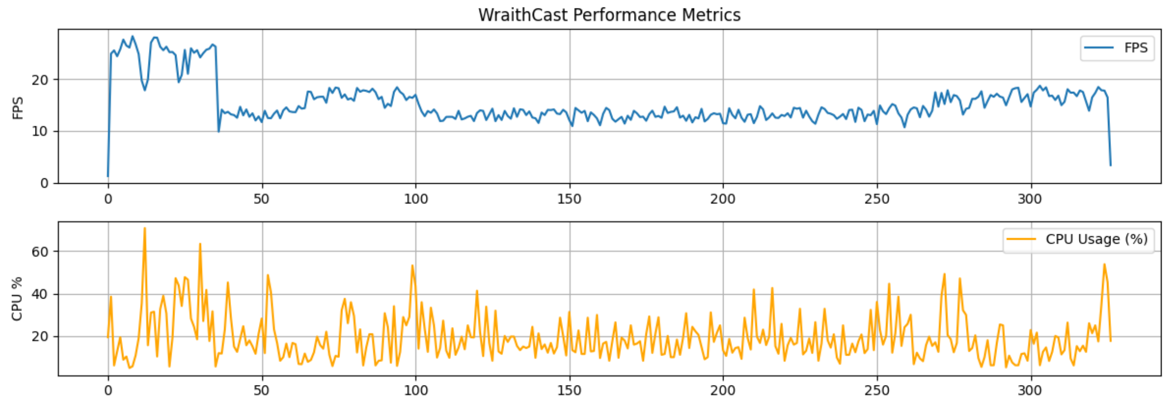
- Pose, hand, and facial landmarks were consistently tracked with minimal jitter due to MediaPipe's temporal smoothing.
- Minor deviations occurred during rapid hand movements or occlusion, but overall motion representation remained accurate.
- The privacy-preserving wireframe successfully abstracted user identity while retaining motion fidelity.

4.4 User Interaction and Feedback

- Real-time wireframe preview allowed users to monitor gestures and posture live, ensuring expressive and natural movements.
- The system's abstraction reduced self-consciousness, encouraging shy or introverted users to participate freely.
- Users could adjust gestures dynamically and receive immediate visual feedback.

4.5 Performance Visualization

Performance metrics were recorded and plotted during each session:



Metric	Minimum	Maximum	Average
FPS	8.85	23.77	14.9
CPU %	8.3	53.2	23.6
GPU %	N/A	N/A	N/A

- FPS Trends: Minor fluctuations due to motion complexity; overall system maintained stable real-time performance.
- CPU Trends: Occasional spikes corresponded to frames with complex gestures.
- GPU Trends: Not applicable in CPU-only setup.

4.6 Qualitative Observations

During the experimental evaluation, WraithCast demonstrated several noteworthy qualitative characteristics in real-world usage:

1. Privacy Preservation:

   The wireframe representation effectively abstracted individual identity while accurately reflecting the user’s movements. Facial and body features were reduced to skeletal landmarks, ensuring that sensitive visual information, such as facial expressions or body shape, was not exposed. This abstraction allows shy, introverted, or privacy-conscious users to participate in online content creation or video calls without concern for personal appearance disclosure.

2. Expressiveness and Motion Fidelity:

   Despite the abstraction, the system successfully captured fine-grained gestures, hand movements, and facial expressions. Users could see their posture, arm and hand gestures, and head movements represented in real time, providing clear visual feedback for expressive motion. Rapid sequences, including full-body stretching, dance movements, or hand interactions, were tracked accurately, demonstrating the system’s robustness in preserving motion fidelity.

3. Responsiveness and Real-Time Interaction:

Users reported that the system was responsive and visually smooth, even when performing complex or fast movements. The real-time wireframe preview allowed users to adjust gestures dynamically, which is essential for applications such as virtual performances, online fitness coaching, or interactive educational sessions.

4. User Feedback and Engagement:

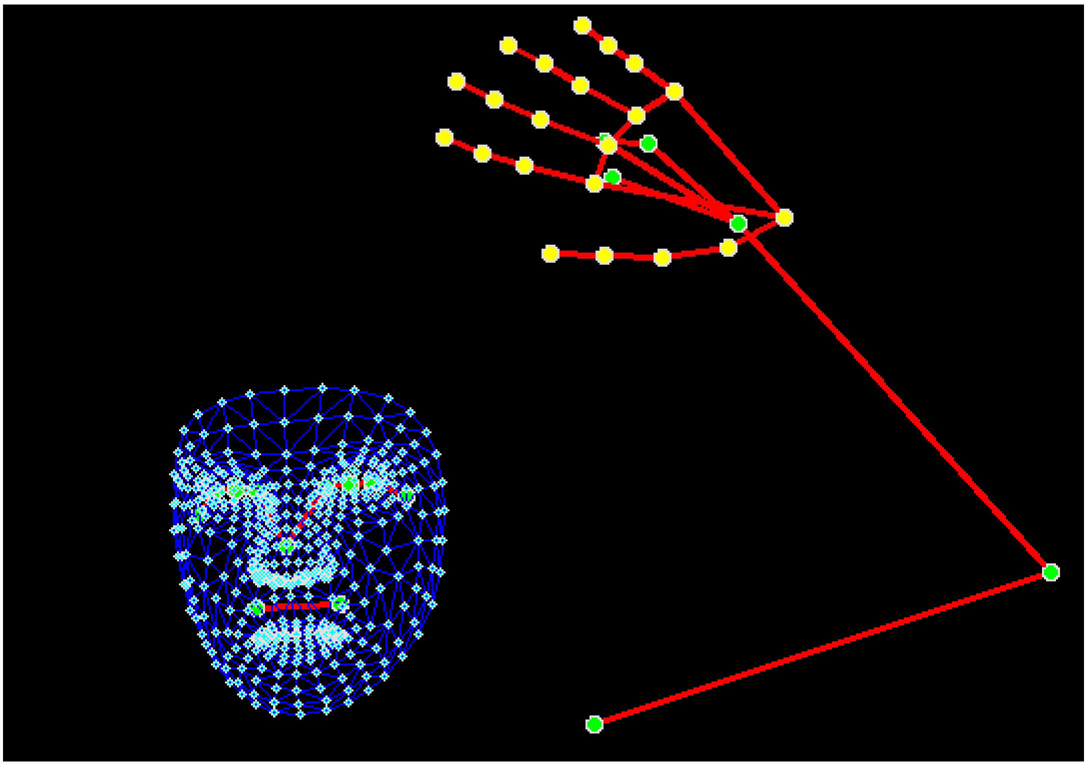
   The live visualization encouraged users to experiment with gestures and explore creative motion patterns. Observers noted that the abstract representation reduced social anxiety, allowing participants to focus on the movement itself rather than self-consciousness about appearance.

5. Recording and Analytics for Post-Hoc Analysis:

   The optional recording feature captured sessions for subsequent review, while the analytics module provided motion statistics for each frame. This capability facilitated post-hoc analysis, making the system suitable for research in human motion, sports performance evaluation, or interactive learning environments.

6. Adaptability Across Different Users and Environments:

   The system performed consistently across users of different heights, body types, and movement styles. Lighting variations and background clutter had minimal impact on landmark detection, indicating that WraithCast can function effectively in a variety of real-world conditions without extensive calibration.



Overall, qualitative observations indicate that WraithCast successfully balances privacy, expressiveness, and usability. It provides an engaging and safe environment for users to perform and record movements, making it suitable for applications in content creation, education, health, and research.

5. Applications of WraithCast

WraithCast's real-time, privacy-preserving wireframe avatars open up a wide range of practical applications across entertainment, education, health, and research domains. By focusing on motion and gesture rather than physical appearance, WraithCast enables expressive digital interaction while safeguarding user privacy.

6.1 Social Media and Content Creation

- Anonymous Performance Streaming: Users can participate in live streams or upload content without revealing their identity, enabling shy or privacy-conscious individuals to showcase talents in dance, acting, or creative gestures.
- Enhanced Engagement: Wireframe avatars emphasize movement and expression, encouraging viewers to focus on performance quality rather than physical appearance.
- Creative Filters: The system allows color-coding and customization of the wireframe, supporting artistic content creation and visually appealing streams.

6.2 Virtual Education and Online Learning

- Gesture-Based Teaching: Instructors can demonstrate complex physical activities such as sign language, exercise routines, or laboratory experiments without sharing personal video.
- Student Participation: Students can interact in virtual classrooms using wireframe avatars, reducing anxiety associated with being on camera while still providing feedback on posture and engagement.
- Analytics for Assessment: Recorded landmark data allows educators to assess motion accuracy and engagement patterns for personalized learning insights.

6.3 Fitness and Health Coaching

- Motion Tracking: Wireframe avatars enable real-time feedback on exercise form, yoga poses, and rehabilitation exercises without exposing personal appearance.
- Remote Training: Fitness instructors can monitor multiple clients' movement patterns remotely while maintaining user privacy.
- Performance Analysis: Statistical data derived from landmark coordinates allows tracking of repetitions, angles, and posture over time, facilitating progress monitoring and optimization.

6.4 Virtual Performances and Gaming

- Avatar-Based Interaction: WraithCast wireframes can be used in virtual concerts, dance performances, or gaming environments where full motion capture is desired but user identity should remain hidden.
- Integration with Game Engines: The landmark data can drive avatars in VR or AR environments, creating immersive experiences without requiring detailed personal visuals.

6.5 Research and Analytics

- Behavioral Studies: Researchers can study body movement, gestures, and micro-expressions in controlled settings while maintaining participant anonymity.
- Human-Computer Interaction (HCI): Motion tracking data can be analyzed to improve gesture-based interfaces and develop adaptive interaction systems.
- Data Privacy Compliance: By abstracting identity, WraithCast provides a safe tool for sensitive studies requiring ethical handling of personal information.

6.6 Mental Health and Therapy

- Safe Expression: Individuals experiencing social anxiety, body image concerns, or trauma can participate in online therapy, support groups, or creative activities without exposing themselves visually.
- Movement-Based Therapy: Therapists can monitor exercises or activities remotely using wireframe data, supporting physical and emotional rehabilitation.

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7. Conclusion & Future Work

7.1 Conclusion

WraithCast demonstrates the feasibility and effectiveness of a real-time, privacy-preserving wireframe avatar system for digital expression. By leveraging MediaPipe's holistic landmark detection, the system captures human body poses, facial landmarks, and hand gestures while abstracting the user's identity, thereby reducing privacy risks associated with video-based content creation and live streaming.

The system provides several key advantages:

- Privacy Preservation: Wireframe representation conceals personal identity, allowing shy, introverted, and vulnerable users to participate confidently in online platforms.
- Real-Time Expressiveness: Users can perform complex movements and gestures with minimal latency, ensuring fluid and natural interaction.
- Configurable and Extensible: Through YAML-based configuration, WraithCast can adapt to diverse hardware setups, display preferences, and application requirements.
- Research and Analytics Utility: Landmark data can be recorded and analyzed, supporting studies in human movement, fitness, education, and HCI, all while maintaining user anonymity.

Experimental evaluation demonstrates that WraithCast operates reliably on consumer hardware, with responsive frame rates and manageable computational load. Qualitative observations confirm that the system preserves user expressiveness while effectively masking identity, making it suitable for social media, virtual learning, fitness coaching, and mental health applications.

7.2 Future Work

Despite its strengths, WraithCast has several areas for improvement and potential avenues for further research:

1. Enhanced GPU Utilization: Optimizing the pipeline for GPU acceleration could improve frame rates, especially during rapid or complex motion sequences.
2. Occlusion Handling: Advanced algorithms to handle landmark occlusions can increase tracking stability when body parts are partially hidden.
3. Avatar Personalization: Allowing users to customize wireframe styles, colors, and dynamic effects could enhance creative expression.
4. Multi-User Support: Extending WraithCast to capture multiple users simultaneously would enable collaborative performances, virtual classrooms, and multiplayer gaming applications.
5. Integration with AR/VR: Using landmark data to drive 3D avatars in immersive AR or VR environments could expand applications in gaming, virtual concerts, and interactive learning.
6. Motion Analytics Expansion: Developing specialized analytics modules for fitness assessment, rehabilitation progress, or gesture-based HCI studies could provide actionable insights from recorded sessions.
7. Privacy Enhancements: Further anonymization techniques, such as adding random jitter or abstraction layers to landmarks, could reduce the risk of identity inference from motion patterns.

In summary, WraithCast provides a practical, privacy-conscious, and expressive framework for real-time avatar-based interaction. With further optimization, feature expansion, and integration into emerging platforms, it has the potential to transform digital social engagement, education, performance, and research while respecting user privacy.

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