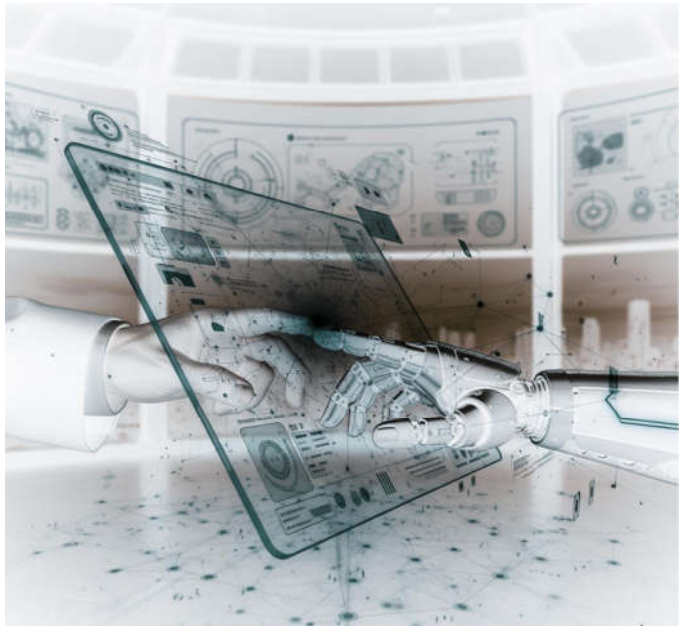


Human-Machine Interaction

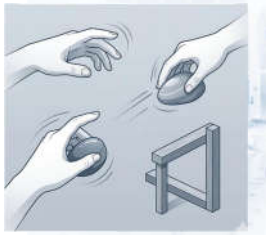
Interaction Modalities & Technologies

Motion Interaction

Dr. Patrick Chan
patrickchan@scut.edu.cn
South China University of Technology

Traditional Input Devices

- Requires **physical contact with an interface surface**
  - **Keyboard** → symbolic, discrete input
  - **Mouse** → indirect spatial control
  - **Touchscreen** → direct manipulation on surface
- However, humans interact with the physical world **without surfaces**



Limitation on Traditional Input Devices

Motion Skill Mismatch

- **Mapping gap** between action and intention
  - **Humans** evolved for grasping, pointing, rotating, and throwing. Hand has 27 DoF
  - **Traditional interfaces** require typing symbols, cursor translation, and tapping icons. A mouse has 2 DoF
- Example: Rotating a 3D object
  - Mouse: drag + modifier keys
  - Human instinct: rotate hand

Limitation on Traditional Input Devices

Surface Dependency

- Keyboard / mouse / touch need **surface**
  - E.g. desk, screen, reachable panel, and clean environment
- Interaction breaks when surface disappears
  - E.g. driving, surgery, public displays, and VR/AR

Limitation on Traditional Input Devices

Attention Demand

- Precise input needs **visual confirmation**:
  - Typing accuracy
  - Cursor positioning
  - Button targeting
- Causes **danger** in vision demanding tasks: driving, piloting, and walking navigation

Limitation on Traditional Input Devices

Need for Touchless Interaction

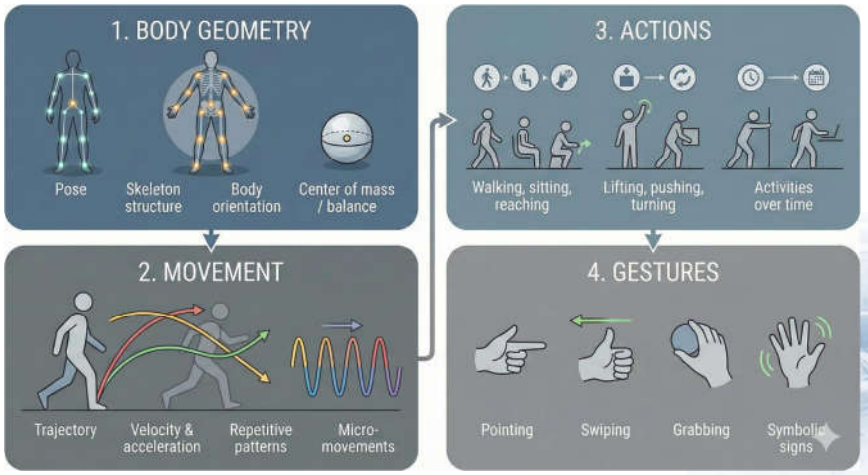
- **Sterile Operating Room**
  - Surgeons browse MRI/CT
  - Avoids touching screens → preserves sterility
- **Industrial Maintenance (AR)**
  - Technician confirms steps
  - No need to release tools
- **Smart Kitchen**
  - Cook flips recipe pages
  - Gands covered in flour → preserves sterility

Motion Capture (Mocap)

- Process of recording the **movement** of objects or people
- **Goal**: To map **physical spatial changes** into a **digital coordinate** system
- Key Parameters
  - **Position** ($x, y, z coordinates)
  - **Orientation** (Roll, Pitch, Yaw)
  - **Dynamics** (Velocity and Acceleration)

Motion Capture

What can be captured?



Motion Capture: What can be captured?

Levels of Motion Understanding

- **Body Geometry** → Raw physical **pose** data
  - Joint positions, skeleton, posture
- **Movement** → How the **body moves**
  - Trajectory, speed, acceleration
- **Actions** → What the person is **doing**
  - Activities over time (walking, sitting, lifting)
- **Gestures** → What the person wants to **communicate**
  - Meaningful motions (point, swipe, thumbs-up)

Motion Capture: What can be captured?

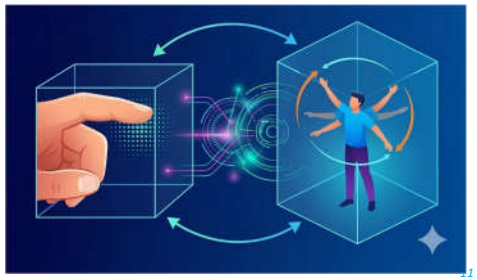
Static vs Continuous Gestures

- **Static Gestures**: Focus on **Spatial arrangement**
  - One-time command. Trigger event
  - E.g. "OK" sign → take photo
- **Dynamic Gestures**: Focus on **Velocity**, **Direction**, and **Rhythm**.
  - System tracks motion continuously
  - E.g. moving a virtual joystick
- **Hybrid Interaction**: Combine **both** types
  - E.g. "Grab" (start) → Move hand (control) → Release (stop)

Motion Capture: What can be captured?

Hand vs Body Gestures

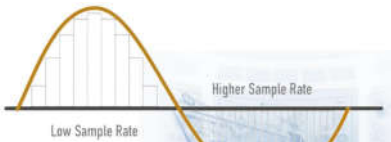
- **Body Gestures**
  - Large-scale, lower precision
  - Navigation, gaming, robot signaling at distance
- **Hand Gestures**
  - Small-scale, high precision
  - Fine control (virtual sliders, typing, object manipulation)
- **Resolution Challenge**
  - System must handle very different scales
    - ~1 cm finger movement
    - ~1 m body movement



Motion Capture: What can be captured?

Quantization

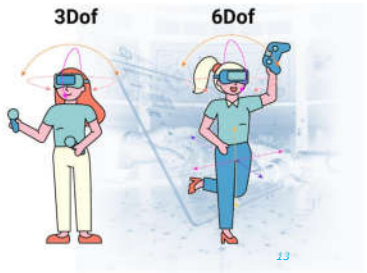
- Human continuous motion is **converted** into small discrete steps
  - **Sampling Rate**
    Faster motion needs faster sensing
    - **~30 Hz** →
      smooth enough for UI interaction
    - **+120 Hz** →
      needed for fast motion analysis (sports, medical)



Motion Capture: What can be captured?

Quantization

- Human continuous motion is **converted** into small discrete steps
  - **Degrees of Freedom (DoF)**
    More complicated actions need larger DoF
    - **3-DoF**:
      rotation only
      (look / tilt / turn)
    - **6-DoF**:
      rotation + position
      (move forward, backward, sideways)



Motion Capture: What can be captured?

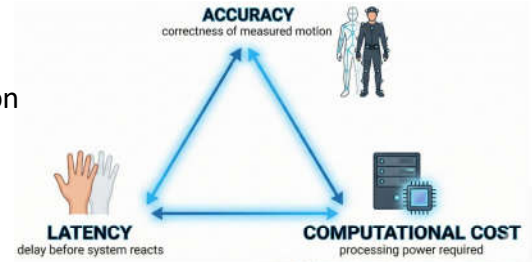
Offline vs Real-Time

- **Offline (Post-processing)**
  - Priority: **precision**
  - Used in filmmaking (e.g., performance capture)
  - Errors can be corrected manually
- **Real-Time (Low Latency)**
  - Priority: **speed & responsiveness**
  - Used in VR/AR and robotics control
  - If latency > ~20 ms → users feel delay

Motion Capture

Trade-off

- Constraints Triangle
  - **Accuracy**
    correctness of measured motion
  - **Latency**
    delay before system reacts
  - **Computational Cost**
    processing power required



- Trade-off example:
  - High accuracy often requires heavy calculation
  - Low latency may result in bad quality

Motion Capture

Devices & Sensors

- **RGB camera**
  standard video tracking
- **Infrared (IR) camera**
  low-light / marker tracking
- **RGB-D camera**
  color + depth
- **Stereo camera**
  depth from two cameras
- **Laser / LiDAR**
  precise distance scanning
- **Time-of-Flight (ToF)**
  measures light travel time
- **IMU**
  accelerometer + gyroscope + magnetometer
- **Radar (mmWave)**
- **Ultrasonic tracking**
- **Magnetic tracking systems**
- **RF / Wi-Fi sensing**

RGB Camera

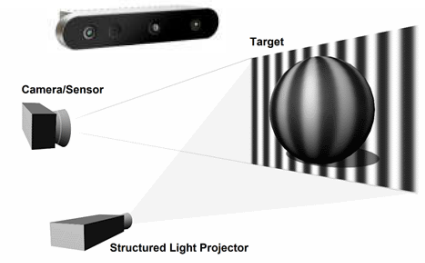
- A standard color camera that captures images in visible light
- **How It works**
  - Captures RGB lights by channels
  - Combines channels to form a full-color 2D image
- **What It Can Detect**
  - Visible light
  - Body pose & skeleton (+AI)
  - Hand gestures (+AI)
  - Facial expressions (+AI)

RGB Camera

- **Strengths**
  - Low cost & widely available
  - No wearable devices required
  - Rich visual information
- **Limitations**
  - Sensitive to lighting conditions
  - Occlusion problems (blocked view)
  - Depth estimation is indirect

RGB-D (Color+Depth) Camera

- A camera that captures both color image and depth distance
- **How It Works**
  - Structured light or Time-of-Flight measures distance to each pixel
  - Produces a 3D scene map
- **What It Can Detect**
  - **All RGB camera can do**
  - **Object interaction depth**
  - Accurate body skeleton tracking (+AI)
  - Hand position in 3D space (+AI)



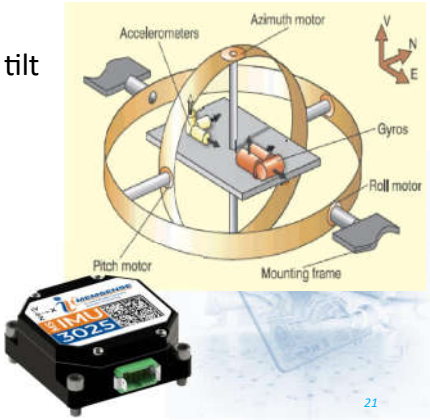
RGB-D (Color+Depth) Camera

- **Strengths**
  - Direct 3D measurement
  - More reliable than RGB alone
  - Works in moderate lighting
- **Limitations**
  - Limited range
  - Sensitive to sunlight/reflective surfaces
  - Higher cost than RGB camera

Motion Capture: Devices & Sensors

Inertial Measurement Unit (IMU)

- A small sensor that measures motion using internal physical forces
- **How It Works**
  - **Accelerometer** → linear movement & tilt
  - **Gyroscope** → rotation
  - **Magnetometer** → orientation
- **What It Can Detect**
  - Device orientation (roll, pitch, yaw)
  - Steps & gait
  - Hand and body motion
  - Sudden impacts / falls



Motion Capture: Devices & Sensors

Inertial Measurement Unit (IMU)

- **Strengths**
  - Works without cameras
  - Not affected by lighting
  - High speed & low latency
- **Limitations**
  - Drift over time
  - Needs calibration
  - Limited absolute position tracking

Motion Capture: Devices & Sensors

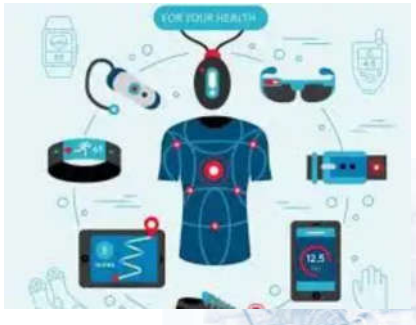
Optical Marker

- **Reflective "ping-pong" balls** placed on anatomical joints to reduce the dependence on object recognition
- **Pros**
  - Extreme sub-millimeter accuracy
  - High frame rates
- **Cons**
  - Expensive setup cost
  - Setup required

Motion Capture: Devices & Sensors

Wearable Device

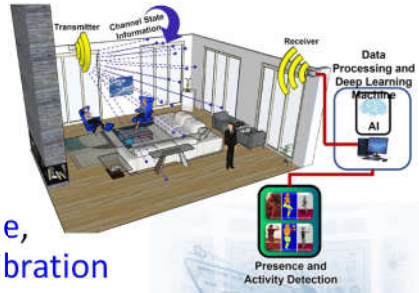
- Devices worn on the body
- **Pros**
  - High precision & stable tracking
  - Works without cameras or lighting
  - Robust to occlusion
- **Cons**
  - Must wear equipment
  - Comfort & battery constraints
  - Setup/calibration required



Motion Capture: Devices & Sensors

Unobtrusive Contactless Detection

- User behaves normally
  - No physical touch
  - No markers or wearable devices
  - No explicit instruction required
- **Pros**: Natural interaction, Comfortable, Hygienic, Minimal user effort, No calibration
- **Cons**: Lower precision than wearables, Sensitive to environment (lighting, occlusion), Privacy concerns



Motion Capture: Devices & Sensors

Application-Driven Selection

- **No "best"** motion capture device
- Different applications require different priorities: Precision, Latency, Robustness, User comfort, Budget,
- Environment constraints
  - **Lighting:** Bright sunlight / Indoor controlled
  - **Occlusion:** Crowded / Clear view
  - **Mobility:** Moving user / Fixed space

Motion Capture: Devices & Sensors

Application-Driven Selection

- Human **comfort** → contactless sensing
- **Precision** → wearables / markers
- **Safety-critical** → low latency sensors
- **Long-term** monitoring → unobtrusive sensing

Motion Capture: Devices & Sensors

Application-Driven Selection

Application	Priority	Suitable Devices
VR/AR interaction	Low latency	IMU, RGB-D
Medical surgery	Sterile & precise	IR, RGB-D, Optical tracking
Sports analysis	High accuracy	Optical MoCap, High-speed cameras
Smart home	Convenience	RGB camera, Radar
Industrial work	Hands occupied	Wearables, Radar
Public kiosk	No contact	RGB-D, LiDAR

Motion Capture: Devices & Sensors

Application-Driven Selection

- **Scenario A**
  - Tracking a professional athlete's gait
  - Optical Markers
- **Scenario B**
  - Controlling a smart TV from a sofa
  - Depth + Vision
- **Scenario C**
  - VR gaming in a living room
  - IMU + Vision

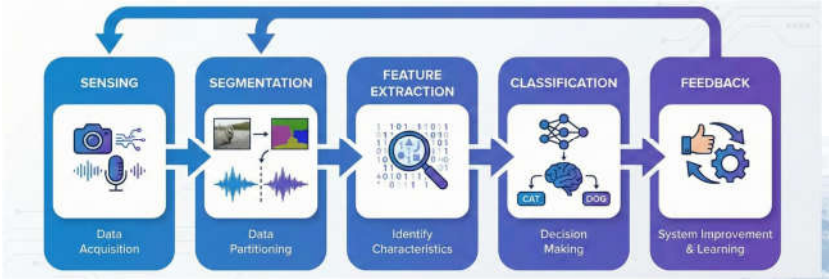


Recognition Pipeline

- **Motion Capture is more than detection**
  - It does not only detect movement
    It interprets human intention
- **AI transforms movement into meaning**

Recognition Pipeline

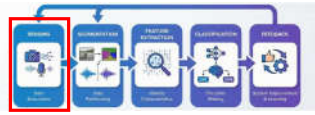
- **Recognition Pipeline**



- Which part is the hardest?

Recognition Pipeline

Sensing



- Sensors capture raw motion data
  - Not only visual information
- **Output**
  Large continuous data stream
- **Challenge**
  Noise, occlusion, drift

Recognition Pipeline

Sensing (Hardware Design)

- In practice, the hardest part is not the algorithm but **data collection**
  - Garbage In, Garbage Out
- Common Problems: Noise, misuse
- Even advanced AI fails if input data is unreliable
- How can we collect high-quality motion data?

Recognition Pipeline

Sensing (Hardware Design)

- **Sensing Volume**
  - Define the interaction zone clearly
  - User must stay inside reliable detection region
  - Too near / too far reduces accuracy
- **User Factors**
  - Wearing position consistency
  - Body occlusion
  - Multiple users in space
  - Natural movement variability

Recognition Pipeline

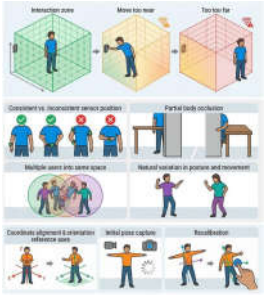
Sensing (Hardware Design)

- **Calibration**
  - Coordinate alignment
  - Orientation reference
  - Initial pose capture
  - Periodic recalibration needed
- **Mounting & Placement**
  - Stable mounting reduces noise
  - Align sensor with expected motion direction
  - Avoid vibration and moving supports

Recognition Pipeline

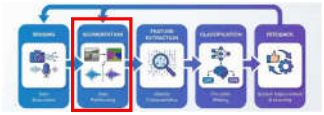
Sensing (Hardware Design)

- **Environment Conditions**
  - Lighting affects optical sensors
  - Metal & interference affect RF sensors
  - Magnetic disturbance affects IMU
  - Temperature may affect precision devices

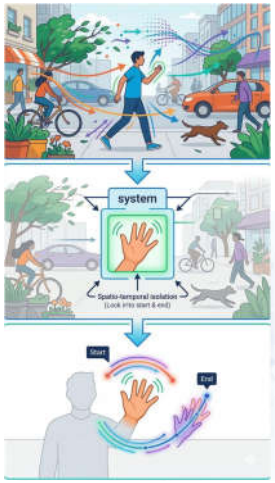


Recognition Pipeline

Segmentation



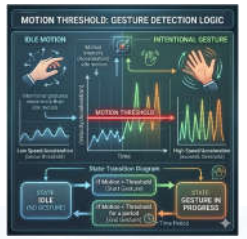
- Extract the related information
  - **Temporal:** when motion starts and ends
  - **Spatial** : Region of Interest (ROI), Position
  - Without segmentation, the system reacts to too much irrelevant information
- **Goal: Separate** meaningful motion from background

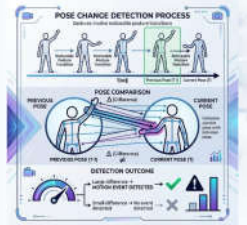


Recognition Pipeline: Segmentation

Temporal Segmentation Method

- **Motion Threshold** (speed/acceleration)
  - Intentional gestures move more than idle motion
  - Monitor velocity / acceleration
    If motion > threshold → start gesture
    If motion < threshold for a period → end gesture
- **Pose Change Detection**
  - Gestures involve noticeable posture transitions
  - Compare current pose with previous pose
    Large difference → motion event detected

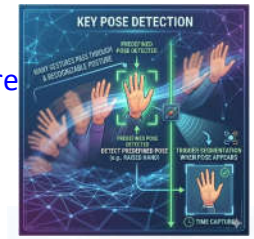




Recognition Pipeline: Segmentation

Temporal Segmentation Method

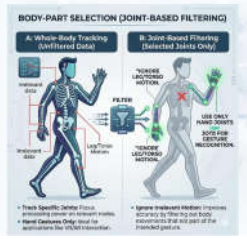
- **Key Pose Detection**
  - Many gestures pass through a recognizable posture
  - Detect predefined pose (e.g., raised hand)
    Trigger segmentation when pose appears
- **Wake Gestures** (raise hand, hold still)
  - System should only listen after explicit intention
  - Wait for special gesture (hold hand up, open palm)
    Enable recognition mode until inactivity timeout



Recognition Pipeline: Segmentation

Spatial Segmentation Method

- **Region of Interest (ROI) Filtering**
  - Only monitor motion inside a predefined interaction
  - Track only the hand zone in front of a screen
    Ignore background or body movement
- **Body-Part Selection** (Joint-Based Filtering)
  - Track specific joints instead of the whole body
  - Use only hand joints for gesture recognition
    Ignore legs and torso motion



Recognition Pipeline

Feature Extraction

- **Convert** raw data into measurable characteristics
  - E.g. Hand trajectory, Speed, Angle change, Motion direction
- Reduce data size but keep important information
- Raw pixels → numerical descriptors

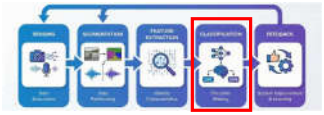
Recognition Pipeline: Feature Extraction

Example

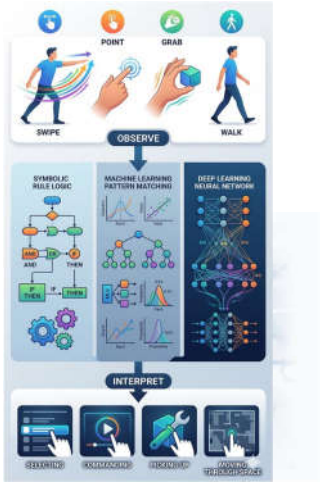
- **RGB-D Camera**
  - Raw data: 3D joint positions
  - Extracted features: hand trajectory, joint angles, reach distance
- **Radar Sensor**
  - Raw data: reflected signal over time
  - Extracted features: velocity profile, presence & motion pattern, micro-movement

Recognition Pipeline

Classification



- Identify the meaning of the motions
  - E.g. Swipe, Point, Grab, Walk
- **Methods**
  - Rule-based
  - Machine learning
  - Deep learning



Recognition Pipeline

Feedback

- When the user performs a gesture but nothing happens, the user doesn't know why
- **Close Loop Control**
  - Movement → Sensing → Recognition → Feedback → **User Adjustment**
- **Low-Latency Feedback**
  - Attempt to recognize the gesture immediately, even before it's finished

Recognition Pipeline

Feedback

- **Visual Feedback**
  - E.g. highlight object, progress indicators
- **Auditory Confirmation**
  - E.g. Tone on success, warning sound
- **Haptic Cues**
  - E.g. Vibration on activation

Recognition Pipeline

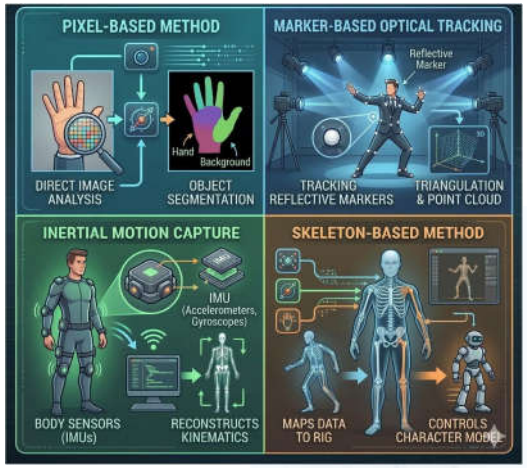
Feedback & Interaction Loop

- Response when recognition failed
- **Diagnostic Feedback**
  - Tell the user why it failed: “Too fast”, “Too far”
- **Confidence Scores**
  - Execute command only if confidence > 90%
  - Otherwise show hint: “Low confidence — try again”

Recognition

Common Methods

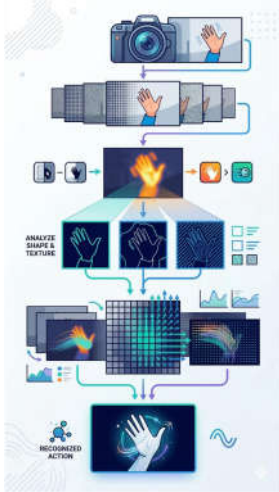
- Pixel-Based Method
- Marker-Based Optical Tracking
- Inertial Motion Capture
- Skeleton-based Method



Recognition

Pixel-Based Method

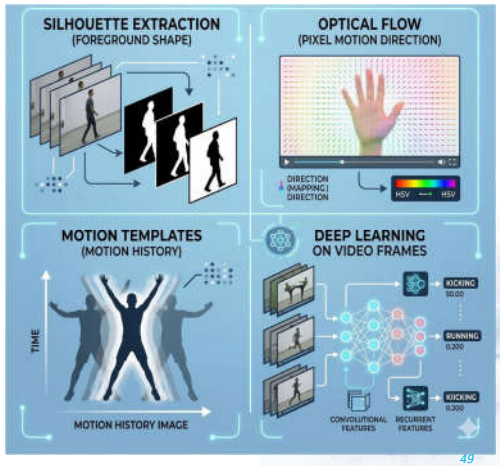
- Recognize motion directly from image pixels
- Process:
  - Detect motion regions
  - Analyze shape or texture change
  - Track pixel movement
- **Output**: action or gesture label



Recognition: Pixel-Based Method

Typical Techniques

- **Silhouette Extraction** (foreground shape)
- **Optical Flow** (pixel motion direction)
- **Motion Templates** (motion history)
- **Deep Learning** on video frames



Recognition: Pixel-Based Method

Characteristics

- **Pros**
  - No body model required
  - Works with ordinary cameras
  - Captures full-body appearance cues
- **Cons**
  - Sensitive to lighting & background
  - Affected by clothing variation
  - Hard to understand precise joint motion

Recognition: Pixel-Based Method

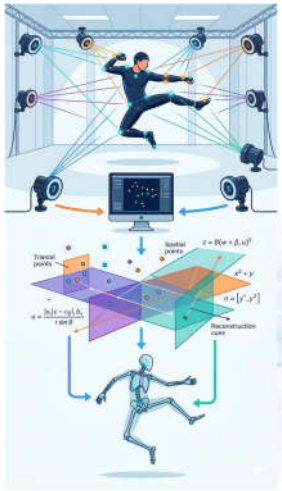
Applications

- **Best for**
  - Activity recognition
  - Surveillance behavior detection
  - Crowd analysis
- **Not ideal for**
  - Fine hand gesture control
  - Precise interaction

Recognition

Marker-Based Optical Tracking

- Track reflective markers attached to the body using multiple cameras
- **Process**
  - Attach markers to key body locations
  - Cameras detect marker positions
  - Triangulate 3D coordinates
  - Reconstruct body motion



Recognition: Marker-Based Optical Tracking

Characteristics

- **Pros**
  - **Gold standard precision**
  - Reliable for biomechanics analysis
  - Suitable for animation & sports science
- **Cons**
  - Requires special suit & setup
  - Expensive multi-camera system
  - Not suitable for everyday environments

Recognition: Marker-Based Optical Tracking

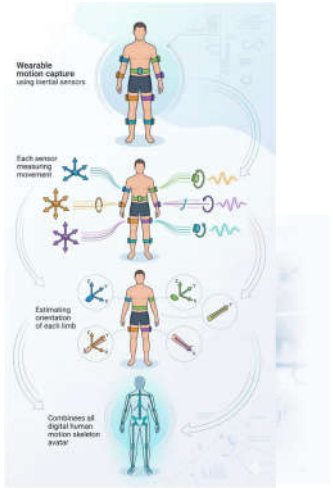
Applications

- **Best for**
  - Film & game animation (highest motion realism)
  - Clinical gait & rehabilitation analysis
  - Professional sports biomechanics research
  - Laboratory human movement studies
- **Not ideal for**
  - Daily consumer interaction (too intrusive)
  - Outdoor or large public spaces
  - Mobile AR/VR use
  - Quick setup environments (factories, homes)

Recognition

Inertial Motion Capture

- Capture human motion using wearable inertial sensors (IMUs)
- Process
  - Attach IMUs to body segments
  - Measure acceleration & rotation
  - Estimate orientation of each limb
  - Combine segments into full-body motion



Recognition: Inertial Motion Capture

Characteristics

- **Pros**
  - Portable and mobile
  - Works indoors & outdoors
  - Low latency response
- **Cons**
  - Position drift over time
  - Requires calibration
  - Wearing equipment can be inconvenient

Recognition: Inertial Motion Capture

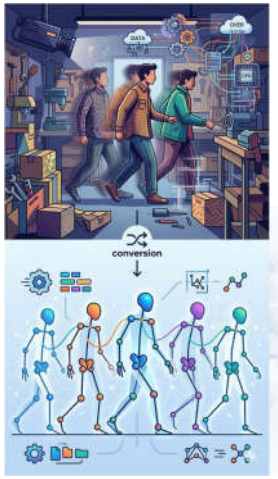
Applications

- **Best for**
  - VR motion capture
  - Outdoor sports analysis
  - Rehabilitation monitoring
  - Robotics teleoperation
- **Not ideal for**
  - High-precision position measurement
  - Casual public interaction
  - Short spontaneous use (setup required)

Recognition: Skeleton-based Method

Problem with Raw Sensor Data

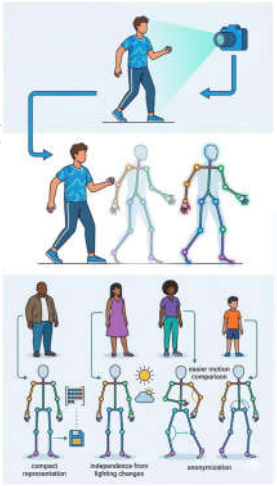
- **Images** contain background, lighting changes, clothing variation
  - Hard for algorithms to directly interpret motion
  - High computational cost
- **Skeleton** methods remove visual complexity so the system understands movement structure



Recognition

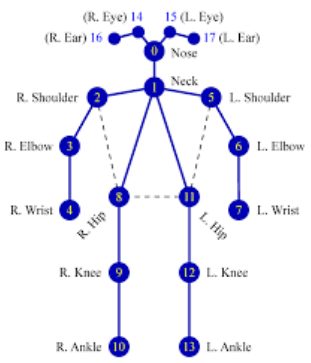
Skeleton-based Method

- Convert the human body into **key joints**
  E.g head, shoulders, elbows, hands, hips, knees, feet
- A skeleton is estimated from sensor data using pose estimation algorithms
- **Input:** RGB images, Depth images, Multi-camera views, Motion sensors (IMU suits)
- **Output:** Set of body joints
  head, shoulders, elbows, hands, hips, knees, feet

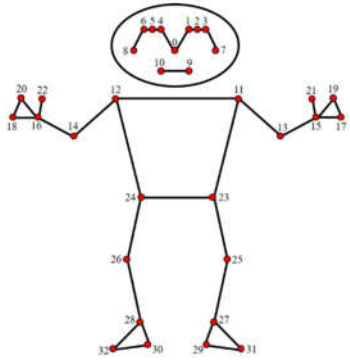


Recognition: Skeleton-based Method

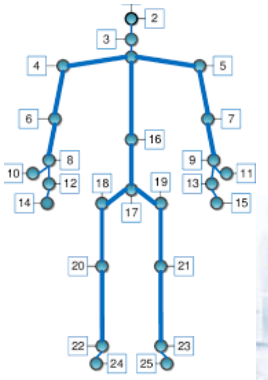
Standard Frameworks (Body)



COCO, Microsoft
(17 points)

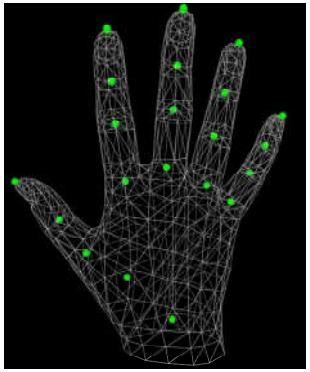


Media Pipe, Google
(33 points)

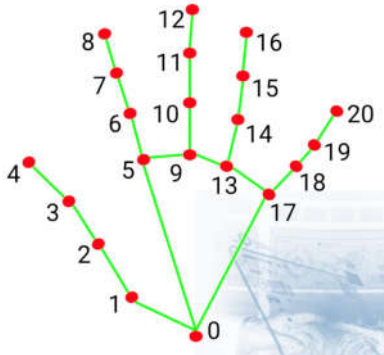


Kinect, Microsoft
(25 points)

Standard Frameworks (Hand)



Mano, Max Planck Institute, Germany
(21 keypoints / mesh)



MediaPipe, Google
(21 keypoints)

Joint Constraints

- Human joints have limited Degrees of Freedom (DoF)
  - **Hinge joints (knee, elbow)**: 1-DoF, Flexion / extension only
  - **Ball-and-socket joints (shoulder, hip)**: 3-DoF, Rotation in all directions
- The constraints improve estimation
  - E.g. Elbow cannot bend backward

Characteristics

- **Pros**
  - Compact representation
  - Robust to clothing & appearance
  - Easier motion comparison
  - Efficient for recognition algorithms
- **Cons**
  - Sensitive to occlusion
  - Reduced finger detail

Applications

- **Best for**
  - Gesture interaction
  - Human–robot interaction
  - VR body tracking
  - Action recognition
- **Not ideal for**
  - Heavy crowd occlusion scenes
  - Exact biomechanical measurement

Recognition

Common Failure Cases

- **Self-Occlusion**
  - Parts of a body block each other
- **Motion Blur**
  - Moves faster than sensor capture rate
    - E.g. Typical cameras (~30 fps) cannot track fast motion
- **Environmental Noise**
  - Shadows or patterned clothing create false detections

Recognition

Dynamic Gesture

- **Static**: recognize a single pose
- **Dynamic**: recognize motion over time
- Extra Challenges
  - **Temporal Segmentation:** Must detect start and end of motion (not only spatial location)
  - **Speed Variation:** Different users move at different speeds
  - **Variable Duration:** Same gesture may last longer or shorter

Recognition: Dynamic Gesture

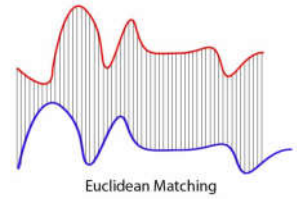
Pre-processing Methods

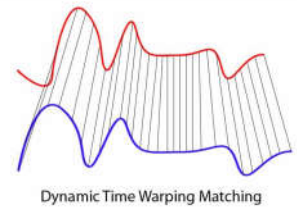
- Normalization
  - **Adjust** time scale so motions become comparable
  - **Align** sequences before classification
- Fitting Variable-Length Data into Models
  - **Zero-Padding**: Add empty frames to short motions
    - Simple but may add noise
  - **Interpolation**: Resample motion to fixed length
    - Smoother but may distort details

Recognition: Dynamic Gesture

Trajectory-Based Recognition

- **Dynamic Time Warping (DTW)**
  - Motion sequence comparison method
    - Still works even if one motion is faster or slower
  - **Spatiotemporal Curves** are used
    - Show motion as a path over time
      - like a line moving through space
    - **Measure**
      - **Curvature**: how much the path bends
      - **Path length**: how far the motion travels





Recognition: Challenges

Generalization

- **Person-Independent Recognition**
  - Works across age, gender, body size, mobility
- **Speed Invariance**
  - Recognize gesture regardless of duration
    Example: swipe in 0.2 s or 0.8 s
- **Background Noise Resistance**
  - Ignore other people or movements in the scene

Recognition: Challenges

Annotation Cost

- Labeling videos requires marking start/end of gestures
  - Extremely time-consuming and expensive at scale
- **Solution: Synthetic Data**
  - Generate motion using game engines (Unity / Unreal) or LLM
  - Produce large amounts of clean data

Recognition: Challenges

Latency

- **Human Perception Limit**
  - 100 ms recognition delay → feels sluggish
  - AR/VR target often <20 ms
- **Computation Budget**
  - Deep networks improve accuracy
  - But limited by mobile/embedded hardware power

Recognition: Challenges

Early Detection

- Recognize the gesture before it finishes
  - Model continuously estimates gesture probability
  - If confidence > 90% → trigger command early
  - Example: detect “Circle” at ~75% completion
- Trade-off: **Accuracy** vs **Responsiveness**

Gesture Design

- Assign meaning to a detected gesture
  - e.g., "Rotate hand" -> "Adjust Volume"
- Simplest Rule on Mapping
  - **Distinguishability**
    Gestures must be easy to tell apart
    - E.g. Two fingers ↑ vs Three fingers ↑

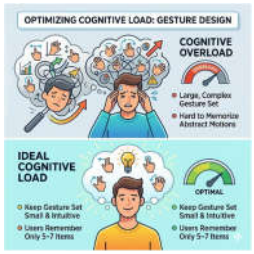
Natural vs Learned Gestures

- **Natural (Intuitive)**
  - Mimicking physical world interactions.
  - **Benefit**: Zero learning curve
  - E.g. Turning a virtual knob to increase volume.
- **Learned (Abstract)**
  - Symbolic movements that must be memorized.
  - **Benefit**: Highly efficient for "power users" once mastered
  - E.g. Drawing an "S" in the air to Save a file.

- **Trade-off:** "Ease of Entry" vs "Expert Efficiency"

Avoiding Overload & Fatigue

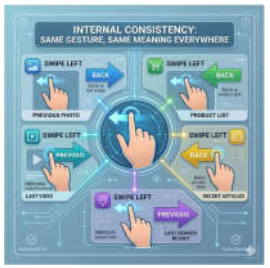
- **Cognitive Load**
  - Keep the gesture set small and intuitive
    - Users can remember only 5–7 abstract gestures



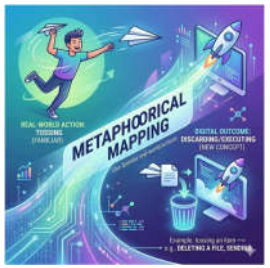
- **Ergonomic Comfort**
  - Avoid high-effort movements (e.g., arms raised overhead)
    - Prevent fatigue during repeated use
  - Relaxation Zone: Prefer gestures near the body
    - E.g. Elbows tucked or resting on a surface

Consistency and Memorability

- **Internal Consistency**
  - Same Gesture, Same Meaning everywhere
  - E.g. swipe left = back



- **Metaphorical Mapping**
  - Use familiar real-world actions
  - E.g. tossing an item



Gesture Design

Inclusivity

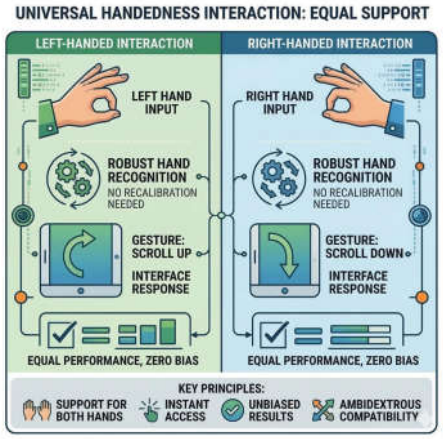
- **Cultural Nuance**
  - Some gestures carry different meanings across regions

- **Body Diversity**
  - Users vary in arm length, hand size, and mobility

Gesture Design

Inclusivity

- **Handedness**
  - Support both left- and right-handed interaction
  - No recalibration or performance bias



Gesture Design

Mapping

- **One-to-One Mapping**
  - One gesture, one meaning

- **Context-Aware Mapping**
  - Same gesture, different meaning
  - Combine gesture recognition with environmental context
    - Example: Pointing
      - Point at TV → "Turn on"
      - Point at person → "Look there"

Unintentional Movements

- **Passive vs Active Movement**
  - **Gesticulation**: natural hand motion while talking
  - **Manipulation**: intentional command to the system
- **Accidental Trigger**
  - E.g. Reaching for a coffee cup triggers "Delete"
- **Thresholding Techniques**
  - **Dwell time:** action must be held briefly
  - **Minimum velocity:** ignore slow casual motion

Unintentional Movements

Confirmation

- **Two-Step Activation: Prime → Execute**
  - Engagement gesture activates system (e.g., wake gesture)
  - User performs actual command
- **Critical Action Barriers**
  - For high-risk commands (Erase Data / Shut Down), require hold gesture (~3 s)
  - "Undo" Gesture

Unintentional Movements

Context Gating

- **Gaze-Gating**
  - Accept gestures only when user is looking at the interface
  - Combines eye-tracking + gesture sensing
- **Proximity Gating**
  - Enable interaction only within a "sweet spot" distance
    Example: 0.5 m – 1.5 m
- **State Awareness**
  - Disable certain gestures in specific modes
    Example: no "Delete" in View-Only mode

Unintentional Movements

Fail-Safe Interaction Protocols

- **"Freeze" Protocol**
  - If tracking is lost (occlusion / sensor failure)
    - Keep last **safe** state
    - Do NOT guess the user's intent
- **Emergency Stop**
  - Universal high-priority gesture (e.g., crossed-arms "X")
  - Overrides all commands immediately