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Hand Centered Studies of Human Movement Project

Technical Report 94-1

Human movement tracking technology

A discussion of general issues which must be considered in evaluating human movement tracking systems and a summary of currently available sensing technologies for tracking human movement

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July 1994

Acknowledgement: This work was supported in part by a strategic grant from the Natural Sciences and Engineering Research Council of Canada.

Contents

Summary

Human movement tracking systems can be classified as inside-in, inside-out and outside-in systems.

Inside-in systems are defined as those which employ sensor(s) and source(s) that are both on the body (e.g. a glove with piezo-resistive flex sensors). The sensors generally have small form-factors and are therefore especially suitable for tracking small body parts. Whilst these systems allow for capture of any body movement and allow for an unlimited workspace, they are also considered obtrusive and generally do not provide 3D world-based information.

Inside-out systems employ sensor(s) on the body that sense artificial external source(s) (e.g. a coil moving in a externally generated electromagnetic field), or natural external source(s) (e.g. a mechanical head tracker using a wall or ceiling as a reference or an accelerometer moving in the earth's gravitational field). Although these systems provide 3D world-based information, their workspace and accuracy is generally limited due to use of the external source and their formfactor restricts use to medium and larger sized bodyparts.

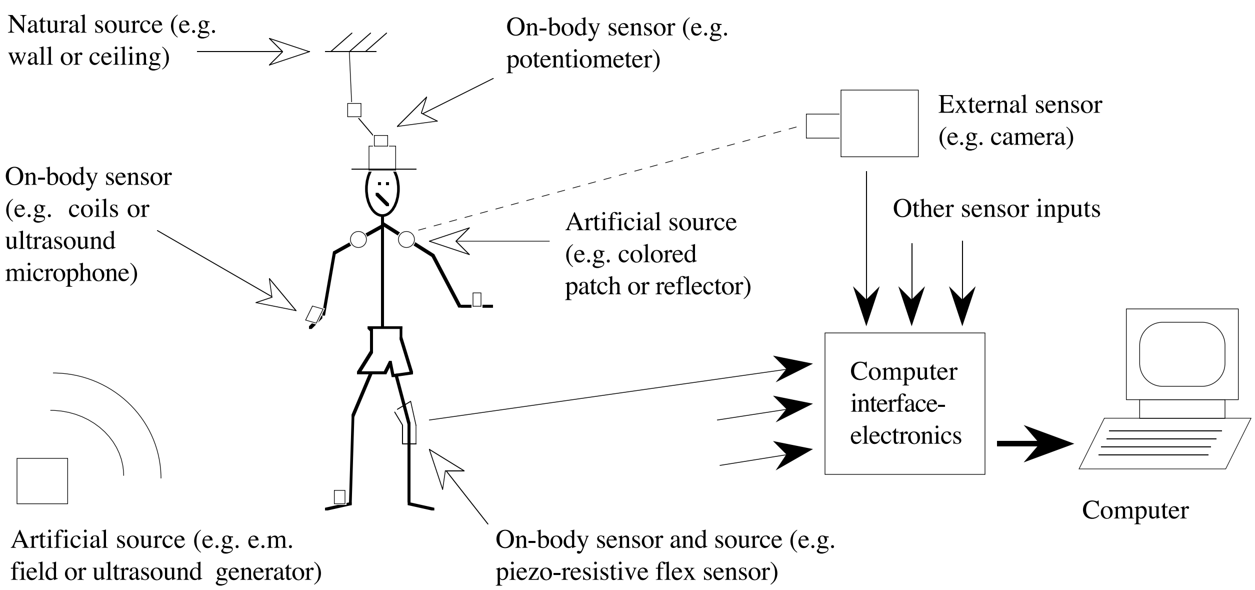
Outside-in systems employ an external sensor that senses artificial source(s) or marker(s) on the body, e.g. an electro-optical system that tracks reflective markers, or natural source(s) on the body (e.g. a videocamera based system that tracks the pupil and cornea). These systems generally suffer from occlusion, and a limited workspace, but they are considered the least obtrusive. Due to the occlusion it is hard or impossible to track small bodyparts unless the workspace is severely restricted (e.g. eye movement tracking systems). The optical or image based systems require sophisticated hardware and software and are therefore expensive.

The strengths and weaknesses of the principles underlying the tracking systems are discussed. A list with descriptive, dynamic, static, precision, interfacing, computational, operational and economic measures is given. Some consideration is given to the application of tracking systems to track various bodyparts. A list of human movement tracking systems, commercial and R&D, and mainly classified by the system's use of medium between sensor and source (acoustical, electromagnetical, mechanical, optical etc.) is available upon request from the author.

General system description

Human movement tracking systems are systems that generate in real-time data that represent the measured human movement. In general such systems consist of the following items, some of which can be omitted, depending on the technology involved (see figure below):

1 - Human
2 - Sensor(s) and/or marker(s) or source(s) + interface-electronics (on body)
3 - Source(s) or marker(s) and/or sensor(s) + interface-electronics (external)
4 - Computer interface-electronics
5 - Computer
6 - Data representing the human movement



Examples of components of human movement tracking systems

Movement of an object is always relative to a point of reference. In order to measure such movement a sensor attached to the object (e.g. a bodypart) can sense (measure the distance to, or orientation or position of) a source attached to the reference or, the sensor, attached to the reference, senses a source that is attached to the object. The human body consists of many moving parts, so that, taking one bodypart as a reference for another, the source and sensor can both be attached to the body. Also, the source can be either natural (e.g. the earth's gravitational field) or artificial (light emitted by an LED). Thus, a taxonomy of human movement tracking systems is possible that extends an existing taxonomy (e.g. Meyer et al 1992):

Inside-in systems: sensor(s) and source(s) are both worn on the body
Inside-out systems: sensor(s) on the body sense(s) external artificial / natural source(s)
Outside-in systems: external sensor(s) sense(s) artificial / natural source(s) on the body

In the case of outside-in systems, artificial sources are usually called markers or beacons, which can be either passive (e.g. light reflectors) or active (e.g. IR LED's).

Other taxonomies have been proposed. The medium of the sensing technology (i.e. acoustical, optical, electromagnetical, mechanical) is often used as a classifier (Ferrin 1991, Meyer et al 1992 and many others). However, inside-in tracking systems are generally not included in this taxonomy. The bodypart (i.e. head, hand, finger, leg, knee, ankle, foot, spine, face, eye, arm, elbow, chest, pelvis, etc.) is also frequently used as a classifier.

Specifying human movement tracking systems

The following measures are proposed for the specification of a human movement tracking system. See also Kalawsky (1993).

Descriptive measures
Medium between sensor and source (acoustical, electromagnetical, optical, mechanical)
Locations of sensor and source (inside-in, inside-out, outside-in)
Type of source (artificial, natural)
Bodypart (finger, hand, arm, shoulder, head, eye, trunk, spine, pelvis, leg, foot, toe)

Static measures
Spatial resolution, range
Static (spatial) accuracy
Linearity, hysteresis, calibration

Dynamic measures
Dynamic accuracy (= static accuracy if system is linear)
Bandwith, frequency range or temporal resolution
Latency, phase lag, update rate or temporal accuracy

Precision measures
Repeatability, stability (drift, artifacts), durability
Noise, EM interference (RF, 60 Hz, ferromagnetic materials, occlusions), filtering, smoothing

Interfacing measures

Sensor interfacing and measurement (AC/DC voltage, resistance, ...)
Power supply
User interface and operating modes
Host communication interface (RS232, RS422, IEEE488, ..)
Wiring (or wireless)

Computational measures

Data frame of reference (joint-based, muscle-based or world-based)
Data format (binary or ASCII format, headers and trailers, ..)
Data representation (angle and muscle tension as a scalar, position as a 3-vector, orientation as euler angles, direction cosines, 3x3 rotation matrices or quaternions, derivatives as ..)

Operational measures

Form factor (size and weight of on-body sensor/cables and additional circuitry)
Workspace size
Comfortability, obtrusiveness
Setup time
Interoperability, compatibility with other systems
Temperature/humidity range

Economic measures

Price
Customer support

Using the above specification measures that are most critical inside-in, inside-out and outside in systems can be compared. However, the comparison is rather crude. See the following pages for more information.

	Inside-in systems	Inside-out systems	Outside-in systems
Spatial resolution	≈ 0.5 - 1 deg	≈ 0.005 - 8 mm ≈ 0.025 - 0.1 deg	≈ 0.0015 - 0.2 % of field of view
Spatial accuracy	≤ 5 deg	≈ 0.8 - 5 mm ≈ 0.1 to 3 deg	≈ 0.004 - 0.5 % of field of view
Bandwith	≤ 80 Hz	≤ 150 Hz	≤ 125 Hz (normally)
Latency	≈ 1 ms (?)	≈ 1 - 40 ms	≈ 1 ms (?)
Precision	medium to high	high	≈ 0.0055 - 0.02 % of field of view
Data frame of ref.	joint/muscle-based	world-based	world-based
Formfactor	ca. 1 cc / sensor-source pair	1-10 cc / sensor > 10 cc / source	< 1 cc / sensor > 10 cc / source
Workspace size	unlimited	natural src.: unlimited art. src.: 1-2 m radius	1-4 m radius
Price (US$)	1-10 k (glove), 30 k (suit)	1-10 k	20-150 k

Inside-in human movement tracking

General remarks

Many of these technologies do not allow for registration of joint-axial rotation (e.g. pronation/supination of the wrist).

All the technologies use body-centered (joint-angle, eye-rotation, muscle-tension) coordinates.

There is no external source or reference necessary, i.e. the workspace is in principle unlimited.

Due to the fact that inside-in systems are worn on the body they are generally considered obtrusive.

Resolution, static/dynamic range, bandwith and latency are all limited by the interface circuitry, generally not by the sensors.

Most of the technologies have small form-factors and are therefore especially suitable for small body parts (finger, eye, toe). For larger bodyparts the accuracy of these technologies may be reduced due to bodyfat.

Bending or flexing sensors across joints involves a transfer of joint angle to the bend angle of the strip which may reduce the accuracy of the technology, although the sensor itself may have a high repeatability. Each individual sensor must be calibrated for each individual user.

See also Sturman (1994) and Kalawsky (1993).

Available technologies

Piezo-resistive flex (Virtex Cyberglove, TCAS Datawear, Mattel/Nintendo Powerglove, Penny & Giles goniometers, GLAD-IN-ART glove, various force-ball devices)
  high repeatability (durable), small

Piezo-electric flex (Mulder 1988)
  medium repeatability (drift), small

Fiber-optic flex (VPL Dataglove, W Industries Spaceglove)
  medium repeatability (low durability due to wear/tear of cracks), computing necessary (nonlinear transfer)

Light-tube flex (Sayre glove, see Sturman (1994))
low repeatability (noise), computing necessary (nonlinear transfer)

Cable extension (+ potentiometer / optical encoder / ..)
high repeatability (?), bulky, obtrusive, possibly limited bandwith, latency and dynamic accuracy

Potentiometers, optical encoders of rotation, goniometers (Virtual reality news WrighTrac)
medium repeatability (mis-alignment errors), bulky, obtrusive

Short range mutual inductance (Motion Orchestration Systems suit and glove)
medium repeatability (noise, interference from ferromagnetic materials), high accuracy, small

Hall effect (Exos Dexterous Handmaster)
medium repeatability (interference from ferromagnetic materials and/or other magnet/sensor pairs), high accuracy

Electro-myographic (BioControl systems EMG interfaces, Bodysynth suit, NTT Cyberfinger glove)
low repeatability and accuracy (noise, drift, artifacts), computing intensive, small, obtrusive

Electro-oculographic (BioControl systems EOG interfaces)
very low repeatability and accuracy (noise, drift, artifacts), small, obtrusive

Nerve potential via nerve cuff
very intrusive, high risk, computing intensive

Inside-out human movement tracking

General remarks

The external source however does provide in most cases 3D, world-based information, i.e. joint-axial rotations can be measured.

The form-factor is in most cases fairly large so that the technologies usually apply to larger bodyparts (i.e. not for eye, finger or toe), imply some obtrusiveness and may have limited accuracy due to inertia of the sensor/receptor (the receiver may shift due to skin/muscle movements). Additionally, there will be some offset introduced due to the receiver size.

Most of the technologies involve some computing which may increase response latency.

Resolution, static/dynamic range, bandwith are all limited by the interface circuitry, generally not by the sensors.

The technologies that use an artificial external source have a limited workspace.

See also Kalawsky (1993), Bhatnagar (1993), Meyer et al (1992) and Ferrin (1991).

In UNC technical report 92-027 a specification for a position and orientation (inside-out) sensor has been proposed that should allow for "ideal" human movement tracking:

- wireless operation
- allow for tracking of multiple users in the same work space without interference
- range of up to 10x10x5 m with reference to a base unit, perhaps the size of a briefcase
- no-wide antenna, ceiling or sensor field required
- latency under 5 ms
- resolution of 1 mm and 0.01 deg
- accuracy of 1 mm and 0.01 deg in registered see through applications, 1 cm and 0.1 deg in nonregistered applications
- sampling rate >= 60 Hz
- direct sensing of state and derivatives

<u>Available technologies (natural source)</u>

Piezo-electric accelerometer (Ladin, 1989 and Doyle, 1993)
medium repeatability (need averaged real-time calibration), interference (gravity field), computing necessary (integration of 3D acceleration), fairly bulky, unlimited workspace, expensive

Gyroscope (solid state, micromechanical or laser, see Doyle, 1993)
medium repeatability (need averaged real-time calibration), small, high latency ?, unlimited workspace, expensive

Inclinometer
only for 2D orientation in vertical plane, (tilt, angle of inclination), limited range, how to separate acceleration from gravity, small ?, unlimited workspace

Magnetic fluxgate compass (Doyle, 1993)
only for 2D orientation in horizontal plane, bulky, unlimited workspace, interference from ferromagnetic materials, slow

Magneto-resistive compass (Doyle, 1993)

only for 2D orientation in horizontal plane, small, unlimited workspace, interference from ferromagnetic materials

Altitude sensor
high latency, low accuracy, unlimited workspace

Available technologies (artificial source)

Potentiometer / optical encoder, externally attached via mechanical linkage (Shooting Star Technology head tracker, Fake Space BOOM, Immersion Probe, Sutherland headtracker, various mice)
high accuracy, high repeatability, low latency (no filtering), bulky, obtrusive/encumbering, small workspace, best useful for free-space movements, compensation necessary for inertia of system

DC EM pulse (Ascension Technology 6DOF tracker)
high accuracy, medium repeatability (interference from the earth's magnetic field and, less, ferromagnetic materials), medium dynamic accuracy (filtering), computing intensive, small workspace, medium latency

AC EM field strength (Polhemus 6DOF tracker)
high accuracy, medium repeatability (interference from ferro-magnetic materials), computing intensive, small workspace, medium latency

AC EM field, phase coherent
high accuracy, medium repeatability (interference from metallic materials), multiple separately located transmitters/receivers

Acoustic time of flight of a pulse (Logitech 2D/6D mouse, Mattel/Nintendo Powerglove, Lincoln Laboratory Wand, Science Accesories Corporation Space Pen)
high latency (lower limit dependent on the airspeed = ca. 0.3 m/ms), multiple separately located transmitters/receivers, low repeatability (speed of sound variations, reflection errors, external ambient noise, occlusion errors), medium dynamic accuracy (filtering), computing intensive, medium size workspace

Acoustic, phase coherent (Piltdown acoustic compass, Seitz-Pezaris head tracker)
medium latency (?), low repeatability (accumulated computing errors, reflection errors, external noise, occlusion errors), multiple separately located transmitters/receivers

On body videocamera capturing IR LED's (U. of North Carolina head tracker)
most applicable for the head, bulky, computing intensive, need special environment, occlusion sensitive, fairly large workspace

Infrared sensing of synchronized rotating beams (Honeywell laser beam helmet tracker)
small working volume

Global positioning systems
low accuracy, unlimited workspace, bulky

Outside-in human movement tracking

General remarks

These tracking technologies are generally the least obtrusive of movement tracking technologies.

Videocamera-based technologies are limited by occlusion. For movements of larger bodyparts this may be solvable, but for e.g. fingers, two closely interacting hands, or two closely interacting persons it remains a major problem.

Videocamera-based technologies are computing intensive due to difficulties with staying locked onto the bodypart or marker and/or the involved transformations of data, so that response latency may be high (especially relevant for eye-tracking).

The performance of videocamera-based technologies is dependent on the type of lens or the field of view of the camera. Videocamera-based technologies are operational in a limited workspace only due to the field of view of the camera(s). If the field of view of one camera is increased, resolution is decreased.

Illumination of the environment may be interfering with proper operation of the system.

Conventional 30 or 60 frames per second technology provides insufficient bandwith, i.e. special highspeed cameras are required.

The amount of instrumentation of image based technologies generally remains the same independent of the number of points tracked.

On-body passive or active markers or beacons have to be attached to the bodypart which introduces an offset. Special care has to taken to select and position a marker.

See also Kalawsky (1993), Bhatnagar (1993), Meyer et al (1992) and Ferrin (1991).

Available technologies (natural source)

Body image analysis

very computing intensive, low repeatability (computer vision technology not reliable)

Pupil tracking (ISCAN RK426, LC technologies Eyegaze, Micromeasurements system)
as above, only for eye

1st-4th Purkinje trackers
for eye only, bulky

Scleral and limbus reflection
for eye only, low repeatability (noise, drift and artifacts due to movements of eyelids, etc)

Shadow image analysis (Artificial reality corp. Videoplace, Vivid Mandala)
as above, only for body(part) outline

Moire pattern
only for body outline

Electrostatic field measurement (as used by Lev Termen, currently researched by Tom Zimmerman and Neil Gershenfeld in the MIT Medialab)

Available technologies (artificial source)

Reflective marker (BTS ELITE, Adaptive Optics Associates Multi Trax, Oxford Metrics VICON, Charnwood dynamics CODA, Optikon MacReflex, Peak Performance technologies PEAK5, HCS Vision Technology Primas, Motion Analysis ExpertVision 3D, Yaman Optfollow 7100, Hentschel HSG, Optron 5600, Origin Instruments head tracker)
medium reliability (marker identification errors), not for small bodyparts (marker identification errors) [also for eye ?]

Infrared LED (Northern Digital Optotrak, Log-In COSTEL, Selspot SELSPOT, Honeywell LED array helmet tracker, United Detector Technology Instrument Group Opeye)
medium reliability (errors due to ambient infrared radiation, marker reflections and geometric errors), medium latency (LED sequencing)

B/W marker pattern (Honeywell videometric helmet tracker)

Color marker pattern (Columbus Instruments Biovision, Dorner 1994)

Tracking a part of the human body

The size of the bodypart can be used to distinguish three different classes of applications of human movement tracking systems: large to medium sized body parts (head, hand, arm, leg, foot, hip, trunk, shoulder), medium to small body parts (finger, toe, jaw), small to tiny bodyparts (eye, lips, nose, ears).

Movements of medium to large bodyparts are usually registered with either inside-out or outside-in systems, although inside-in systems also have been built for this application(e.g. VPL Datasuit).

Movements of medium to small bodyparts are usually registered with inside-in systems.

Registration of eye movements requires specialized solutions. Hallet (1986) and O'Donnel (1986) give a useful, fairly complete, overview of available technologies and Hallet (1986) suggests the following requirements for an eye movement tracking system:

- Accuracy: > 1% or a few arcmin.
- Resolution: 1 arcmin or 1 arcmin/s
- Range: 1 arcmin to 45 deg
- Dynamic range: 1 arcmin/s to 800 deg/s
- Sampling rate: > 200 Hz (allow tracking of 100 Hz movements)
- Latency: < few ms (small enough to allow for stabilization of the retinal image)
- Vergence angle accuracy: a few arc minutes
- Independence of head movements and eye translation
- Extensibiliy to binocular recording
- Compatibility with movement tracking of the head and other body parts
- Independent of subject in use
- Availability of unobstructed field of view with good access to the head and face
- Non-contact measuring method

Commonly used technologies for the tracking of eye movements include:

- Reflected light tracking: limbus trackers are small enough to place within an HMD but may be prone to noise, drift and artifacts.
- Image tracking (1st-4th Purkinje): high-accuracy purkinje trackers almost need a hoist to lift them.
- Magnetic coil: magnetic coils are promising but need pseudo-surgical procedures to mount them in the eye and are very uncomfortable.
- EOG: EOG is barely worth considering as a gaze tracker.

Error sources of eye movement tracking systems include:

- Data transmission lags: Inevitably, it takes a finite time to sample and transmit data from any of these devices. This has proved a problem with head-tracking, but bearing in mind the speed of human eye-movements, even delays of the order of a few msec may produce perceptual instability when coupled with rendering lags.
- Vergence angles: If you want to ascertain where someone is directing his/her gaze in depth, the geometry is obviously critical, and a few arcminutes can make a big difference in estimation, this sets a considerable problem in the face of the accuracy of current tracking technologies.

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