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Off-the-Shelf, Real-Time Human Body Motion Capture for Synthetic Environments (with Supplement)

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Off-the-Shelf, Real-Time, Human Body Motion Capture for Synthetic Environments

(Supplement)

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1. Purpose

The original purpose of the Off-the-Shelf, Real-Time, Human Body Motion Capture for Synthetic Environments [Frey 95] paper was to make recommendations to the Advanced Research Projects Agency (ARPA) on what synthetic environment motion capture technologies to invest in now, in the near term and in the future.

The original paper covered the basics of motion capture technology as it applies to real-time tracking of a human body for synthetic environment applications. It discussed the trade-offs between tracking the entire human body, with its inherent calculational simplicity, and partially tracking the human body, with its inherent lack of user encumbrance. The strengths and weaknesses of all current methods of motion capture were reviewed, including the capability (or lack thereof) of adapting each method to real-time track of the entire human body for synthetic environment applications. Finally, recommendations were made specifying which technologies should be purchased (current), funded (near term), and investigated (far term).

The purpose of this supplement is to relay additional information about electro-magnetic motion capture technology and make additional recommendations as to what should be purchased now for human body motion capture needs for synthetic environment applications. Appendix A details the recommendations made in the original paper. In addition, data on currently-available motion capture systems, included in the original paper, is included in Appendix B for reference purposes.

2. Additional Data

During the authors' original data gathering efforts, it was noted that Ascension Technologies was in the process of producing a multiple sensor, integrated, electro-magnetic motion capture package similar to the integrated system produced by Polhemus, Incorporated, called ULTRATRAK. Ascension's new system was being called MotionStar. The authors were told that it consisted of very similar technology to that used in their Flock of Birds system, but that all of the components were being packaged in one integrated unit for convenience.

The authors were also told, during a visit to Ascension's primary facility in Burlington, Vermont, that no printed information was available for the new system. Because there was no hard copy information available to back up anything the authors' would write, this system was not included in the original paper. Thus, the authors' system of choice remained Polhemus' ULTRATRAK, due to its integrated nature.

Recently, however, Ascension has provided the authors with printed information, including specifications and comparisons with Polhemus' ULTRATRAK system, which warrants additional attention. Figure 1 compares similar configurations of the Polhemus ULTRATRAK system and the Ascension MotionStar system.

Parameter	Ascension MotionStar	Polhemus ULTRATRAK Pro
Maximum Number of Receivers per Unit	20	32
Maximum Number of Networked Units	3 (4-5 planned)	20
Dedicated Processor for Each Receiver?	Yes	Yes, for up to 16 receivers
Interfaces	RS-232 and RS-485 (Ethernet and SCSI planned)	Ethernet and SCSI (dedicated Ethernet recommended)
Maximum Data Transfer Rate	115 kbps per RS-232 Interface	10,000 kbps using Ethernet
Maximum Data Update Rate	120 Hz	16 receivers : 120 Hz 32 receivers : 60 Hz
Latency	~ 8.5 ms	~ 6 ms
Maximum Range	10 feet	15 feet
Accuracy	0.13° RMS 0.7 mm RMS at 5 feet	3° RMS 1" RMS at 5 feet
Resolution	Unavailable but testing in progress	0.1° RMS 0.05" RMS at 5 feet
Metallic Object Distortion	Low	High
Cost per Unit with 16 Receivers	$41,765 (16 rcvrs @ 120 Hz) (24JAN95 Quote)	$71,500 (32 rcvrs @ 60 Hz) $39,500 (16 rcvrs @ 60 Hz) (25JAN95 Quote)

Figure 1 -- Ascension MotionStar / Polhemus ULTRATRAK Comparison

In comparing the characteristics of the Ascension MotionStar system and the Polhemus ULTRATRAK system, one can find strengths and weaknesses in both. While deciding on which system to use, the intended application must be considered.

The Ascension MotionStar system's primary advantage is its resistance to interference from metallic objects in the vicinity of its transmitter or receivers. This interference is caused by the generated magnetic signals creating eddy currents in metallic objects. These circulating currents subsequently create magnetic fields of their own which adversely impact the local magnetic field density in the vicinity of the metallic objects. This effect shows up as measurement distortions in the tracking system.

Ascension's MotionStar system uses pulsed DC magnetic fields. When the field pulse is generated, time is allowed for the DC magnetic field fluctuations to stabilize and the eddy currents in metallic objects to die out. The longer the time delay between magnetic pulse generation and receiver signal measurement, the less distortion is seen in the measurement. Of course, the longer the time delay, the larger the measurement latency and the lower the measurement update rate.

Another of Ascension's advantages is their specified measurement update rate. The MotionStar system provides a maximum 120 Hz update rate regardless of the number of receivers (up to 20) used. This is accomplished by the use of a dedicated processor for each receiver. The Polhemus ULTRATRAK system's update rate is a maximum of 120 Hz for up to 16 receivers. When more than 16 are added, the update rate is degraded, reaching a minimum of 60 Hz when 32 receivers are used. This is because each ULTRATRAK system is capable of housing only 16 processor cards which must be shared by all of the attached receivers.

Among the top of Polhemus' primary advantages is the interface method provided between the ULTRATRAK system and the host computer system. Polhemus' device is capable of being interfaced via Ethernet or SCSI bus. Either method has the potential to provide Polhemus with a significant data transfer speed advantage over the RS-232 / RS-485 serial interfaces employed by Ascension's MotionStar system. The ULTRATRAK system, when interfaced via Ethernet, may be accessed by any system connected to the Ethernet interface for which driver software is available. However, Polhemus recommends a dedicated Ethernet interface between the host computer and ULTRATRAK to maximize system performance.

Currently, Ascension's MotionStar system is capable of utilizing only RS-232C and RS-485 interfaces. Each set of dedicated receiver signal processing hardware has its own RS-232C and RS-485 interfaces. Each receiver's data may be processed and passed through a dedicated serial interface to the host computer, or all receivers' data may be multiplexed through the system's master serial interface. The maximum data transfer rate for one RS-232 serial connection is 115 kbps. Thus, if only one 115 kbps RS-232 interface is used with 10 receivers, the data transfer rate is reduced to 24 position / orientation records per second per receiver (data from Ascension's MotionStar Installation and Operation Guide).

To correct this inconvenience, Ascension has designed an Ethernet / SCSI interface device for its MotionStar system similar to that in Polhemus' system. The first Ethernet-equipped systems are expected to ship in the first quarter of 1996. As an aside, if Silicon Graphics, Incorporated (SGI), systems are to be utilized as the host computers, the Ethernet / SCSI solution is the only practical solution. This is because the typical maximum data transfer rate of the SGI RS-232 interface is 38.4 kbps, which is insufficient for real time, multiple-object tracking applications. The authors have been assured that third party hardware solutions already exist for the conversion of MotionStar RS-232 outputs to allow interfacing via Ethernet.

Polhemus' ULTRATRAK system has a greater physical range of operation than Ascension's MotionStar system. This creates a larger workspace and greater freedom of movement for participants whose bodies are being tracked. Both Ascension's and Polhemus' system will operate outside of their specified maximum ranges but will experience increased degradation in accuracy and performance with increased distance.

3. Supplementary Recommendations

Clearly, the choice of systems requires a serious look into the intended application of the device. While the Polhemus ULTRATRAK Pro system offers an Ethernet interface to the host computer, their system which offers competitive motion capture performance (16 receivers @ 120 Hz) costs $71,500, while the comparable Ascension MotionStar system costs $41,765. While Ascension's system is significantly better at metallic object interference rejection, Polhemus can offer a maximum of 640 sensors tracking individual objects at 60 Hz, while Ascension offers a maximum of 60 sensors tracking objects at 120 Hz.

The host computer / motion capture system interface question cannot be overstated. Most of the synthetic environment applications that the authors have encountered are implemented using Silicon Graphics (SGI) computer systems. The primary external interface device utilized by SGI is Ethernet. SGI's do have an RS-232 serial interface, but this port is typically limited in speed to 38,400bps, and SGI systems are notorious for under-utilizing this interface device. Significant difficulties have been encountered by numerous individuals while trying to interface either of Polhemus' or Ascension's systems with SGI computers via RS-232. This most likely explains why Polhemus' system no longer supports RS-232 and why Ascension is rushing to produce a system supporting an Ethernet interface.

In the author's minds, the interface question is the clear deciding factor. No matter what the application, the interface question is always there. This conclusion leads again to the authors' recommendation of the Polhemus ULTRATRAKPro system.

However, other issues are also of concern. These include location of installation, maximum number of receivers, performance, and cost.

Location of Installation:

In consideration of the intended application, the location of operation must be determined. It is known by both companies that a room free of metallic objects will allow the maximum performance from both systems. In practice, however, this is almost never the case. It may be impossible for the users of a system to completely strip the intended location of motion capture free of all metallic objects. Because of this, Ascension has produced a system which is much less susceptible to metallic object interference.

If the intended location of installation has metallic objects which cannot be removed, and absolute accuracy is important, the authors would tend to recommend Ascension's MotionStar system.

Number of Receivers and Performance:

Polhemus' system allows a maximum of 640 objects to be tracked simultaneously at an update rate of 60Hz. Ascension's system allows 60 objects to be tracked simultaneously at an update rate of 120Hz. While these two numbers of receivers are large, full track of the human body should require no more than about 15 receivers. Both systems will allow the tracking of 15 individual body segments at 120 Hz. Thus, from a practical standpoint, neither system has the advantage.

If the intended application requires that more than 16 objects be tracked as quickly as possible, the author's recommend Ascension's MotionStar system. However, if more than 60 objects must be tracked *at any speed,* the authors recommend Polhemus' ULTRATRAK Pro system.

Cost:

While cost is sometimes not a concern, especially if performance is the deciding factor for an application, the authors feel that it is prudent to mention that Ascension's system costs significantly less when two comparably equipped systems are compared. The authors have tended to use a 16 sensor system as a benchmark from the beginning. When this benchmark system is considered, Ascension has the definite cost advantage ($41,765 vice $71,500).

Final Recommendation:

The primary concern in the authors' minds is ease of interface, utilizing Ethernet and SCSI for maximum data transfer rates. From a practical standpoint, the maximum number of receivers, highest update rate, best accuracy, or lowest cost doesn't mean anything if the system can't get the data to the host computer at a reasonable rate.

While it may not be appropriate for every application, the authors recommend Polhemus' ULTRATRAK Pro system for off-the-shelf, real-time, human body, synthetic environment motion capture applications.

Appendix A

Recap of Original Recommendations

Examination of the current methods of human body tracking (See Appendix B) reveals that there are very few solutions which will provide the real-time, *full* body tracking capabilities described in section 2 (motion capture fundamentals). Some of the systems, while fast enough to provide real-time tracking, cannot track more than a few objects simultaneously. Others can track many objects simultaneously, but are incapable of providing real-time tracking. Mechanical tracking systems typically fall into the former category, while optical, image-based and acoustic tracking systems typically fall into the latter.

This section summarizes the advantages and disadvantages of several current body tracking systems and makes recommendations for application of these technologies to real-time, full human body tracking for synthetic environment applications.

A. Current Recommendations:

Electromagnetic systems are well suited to tracking the entire human body in real time. They provide accurate, reproducible track of the body in real time. They are simple to set up and operate, consisting of a single stationary transmitter, multiple independent receivers attached to the body being tracked and associated electronics. They have no moving parts and are very durable. The electronics package is fast enough to sample the receivers at rates approaching 120 Hz (the minimum tracking frequency for real-time applications is accepted to be around 30 Hz).

The primary disadvantages of electromagnetic tracking systems are their susceptibility to electromagnetic and metallic object interference, range restrictions resulting from use of a transmitted tracking source and user encumbrance caused by the tether used to transmit tracking data to the host computer system. These disadvantages can be easily overlooked in the short term since most of the current body tracking applications do not require the user to move great distances. However, as the application space of synthetic environments grows, there will be applications which will require the user to be free of movement and range restrictions.

The two companies which currently produce electromagnetic tracking systems are Ascension Technology Corporation and Polhemus, Incorporated. Their methods of electromagnetic tracking are almost identical, with the exception of the source signal. Both use a stationary electromagnetic transmitter and multiple receivers. Polhemus' system uses AC electromagnetic field generation while Ascension uses DC. Ascension claims that their use of pulsed DC fields minimizes metallic object interference. Otherwise, the operating characteristics of the systems are the same.

When used for tracking the entire human body, Polhemus has the clear advantage. Their newest system, ULTRATRAK Pro, allows simultaneous track of the entire human body (up to 16 individual parts) in real time, with all of the components collected in one location. The current version of the ULTRATRAK system is tethered, but an untethered version is under development.

The Ascension "Flock of Birds" system has the ability to track the entire human body in real time. However, their tracking system consists entirely of add-ons to their base system. It is not fully integrated like the Polhemus ULTRATRAK system.

Best Currently-Available System:

Polhemus ULTRATRAK 120

(see Appendix A for more information)

It is the authors' recommendation that the Polhemus ULTRATRAK electromagnetic tracking system be used for current synthetic environment systems requiring real-time, full human body tracking, with Ascension's "Flock of Birds" system as a second choice.

B. Near Term Recommendations:

By far the most attractive solution in the near term (within the next two years) is inertial tracking. This method eliminates *all* of the disadvantages of *all* of the current methods of body tracking. It does this by eliminating the need for a source or an external detector. All of the sensors and electronics required would be carried on the user's body. The data collected about the orientation of the user's body parts would then be transmitted, by wireless means, from the user's body to the host computer, eliminating range restrictions and tethering.

Inertial human body tracking is still in its infancy. Angularis Inertial Technologies is the only company that is currently using this method for human body tracking. Their current application of this technology is limited to head tracking for head-mounted-display orientation. Their sensors are still too bulky for unlimited use on the human body. However, given a year of seriously funded development, the technology would be available for this incredible body tracking option.

The primary disadvantage of inertial body tracking systems is cost. One body part sensor, using current technology, can cost several thousand dollars. As this technology is developed, it is apparent that the cost of each sensor would fall into the range of several hundred dollars, making inertial tracking systems not only desirable, but also affordable.

Best Near-Term Solution:

Inertial Tracking

(see Appendix A for more information)

It is the authors' near-term recommendation that inertial body tracking system research be funded to the maximum extent possible. This technology has the potential to be the absolute best solution for real-time, full human body tracking for synthetic environments.

C. Far Term Recommendations:

It is the authors' opinion that the ultimate body tracking solution will not consist of just one technology. The best body tracking system will eventually (within two to five years) be a hybrid combination of several of the tracking technologies discussed. For example: Although inertial tracking systems solve all of the current problems with the local tracking of the human body, it cannot solve the problem of absolute position of the human body in space.

The ideal "body suit" would be a combination of spread spectrum technologies for overall body position determination, inertial technologies for determining the user's individual body part orientation, bio-feedback technologies for level-of-exertion sensing and CyberGlove-like technologies for detailed hand tracking.

Thus the authors recommend the following for the far-term:

1) Continued investment in inertial body tracking systems research,
2) Continued investment in spread-spectrum position tracking research,
3) Continued investment in bio-feedback technology and
4) Continued research into technologies feasible for incorporation in a hybrid "bodysuit" to be used as an overall synthetic environment interface device.

Appendix B
Current Off-the-Shelf Motion Capture Systems

In the following system descriptions, mention is made of a reference human body tracking system (RHBTS). This is a hypothetical device included as a basis of comparison between the current off-the-shelf systems. Although some of the systems described below do not meet these specifications in one area or another, they should not be dismissed out of hand. The RHBTS is only a reference ideal human body tracking system.

The reference human body tracking system specifications are the following:

- Track articulated Human body of 15 segments
- Minimum DOF: 3 DOF orientation or 3 DOF position of each segment
- Minimum spatial resolution: 0.1 inch at 1 m
- Minimum angular resolution: 0.1 degree at 1 m
- Minimum range: 3 m
- Minimum update rate: 30 Hz
- Maximum data latency: 10 msec

Angularis Inertial Technologies

Contact:	Eric Foxlin
Address:	One Kendall Square, Suite 2200, Building 200, Cambridge, MA 02139
Phone:	(617)621-1563
Fax:	(617)577-1209
e-mail:	foxlin@cdgrle.mit.edu
Method:	Inertial
Overview:	The Angularis VR-360 system uses three orthogonal angular rate sensors, three orthogonal linear acceleration sensors and a two-axis magnetometer in one small device to determine the angular orientation of the user's head. The system incorporates a unique pause-reset scheme during periods in which the user's head is still to correct the output of the device for gyro drift. The linear accelerometers are also used for three DOF position estimation between head position fixes (a kind of dead reckoning). An additional device must be used for accurate determination of the user's head position.
Interface:	RS-232C
Update Rate:	500 Hz
Range:	No range restrictions with optional wireless upgrade (otherwise 20 ft)
Accuracy:	Unavailable
Latency:	< 2 msec
Problems:	Cost
Cost:	$9,200 (Entire system with one sensor unit for head tracking)
RHBTS Cost:	N/A
Guarantee:	One year parts and labor.
Comments:	Currently used for head tracking only, but is extensible in the near term to track the entire human body. This technology has the potential to be the best body tracking system available, with none of the drawbacks of current body tracking methods. Within one year, components will be available which will make an entire body tracking system realizable at a much lower cost.

Ascension Technology Corporation

Contact:	Steven S. Work
Address:	P.O. Box 527, Burlington, VT 05402
Phone:	(802)860-6440
Fax:	(802)860-6439
e-mail:	ascension@world.std.com

Method:	Electro-magnetic, DC signal, stationary transmitter, multiple receivers
Overview:	The Flock of Birds sensor suite measures position and orientation (6DOF) of one or more (up to 30) receivers relative to the stationary transmitter. The transmitting antenna is driven by a pulsed DC signal which aids in reducing metallic-device interference.
Interface:	RS-232 and RS-488 Supports most systems, including PC's
Update Rate:	100-144 Hz
Range:	1 m (3 ft) with standard transmitter 2.5 m (8 ft) with extended transmitter
Accuracy:	0.1 degree resolution at 1 foot
Latency:	8 msec
Problems:	Sourced, tethered, limited range, limited metallic object interference
Cost:	$2,700 (one receiver)
RHBTS Cost:	
Guarantee:	30 day money-back, no questions asked.
Comments:	Ascension's Flock of Birds system clearly has the ability to track the entire human body in real time. While their method and results are very similar to those of Polhemus, Inc., they claim that their use of pulsed DC magnetic fields, rather than AC, makes their devices less sensitive to metallic device interference. [*Supplement: The authors have seen this in practice in a side-by-side comparison of Ascension's and Polhemus' systems at Ascension's factory in Burlington, VT. There does seem to be a significant reduction, in Ascension's systems, in the distortion effects caused by metallic object interference. Also, as covered in the body of this supplement, Ascension has produced a new, integrated tracking system with up to 20 receivers that has a maximum update rate of 120 Hz.*]

BioControl Systems, Incorporated

Contact: Anthony Lloyd
Address: 2555 Park Boulevard, Palo Alto, CA 94306
Phone: (415)329-8494
Fax: (415)329-8498
e-mail: biomuse@well.sf.ca.us

Method: Bio-electric neural signal sensing (bio-feedback)

Overview: The BioMuse system uses bio-electric signals received from the body via semi-aqueous skin-contact sensors. It is capable of detecting electric signals generated for muscular control (EMG), eye control (EOG), heart control (EKG) and brain waves (EEG). Using these bio-electric signals, the BioMuse system is able to synthesize computer system control signals, allowing the user to control the computer via eye-movements, bodily gestures, etc.

Interface: PC serial

Update Rate: nominally 4 kHz
Range: N/A -- no source
Accuracy: N/A -- no reference for bio-electric signals
Latency: Unavailable

Problems: No ability to detect position or orientation, tethered.

Cost: Unavailable
RHBTS Cost: N/A
Guarantee: Unavailable

Comments: The BioMuse system cannot be used for body tracking as such but, when combined with another means of Human body tracking, it provides valuable information about the user such as, eye-position, facial expressions, bodily muscle tension (representing the user's level of exertion). It is the author's opinion that the BioMuse technology should be explored as a potential complement to ANY method of Human body tracking.

Biomechanics, Incorporated

Contact:	Vaughn Cato
Address:	200 N. Cobb Parkway, Suite 142, Marietta, GA 30062
Phone:	(404)424-8195
Fax:	(404)424-8236
e-mail:	gcato@st6000.sct.edu / biomech@crl.com
Method:	Image-based with passive markers
Overview:	The Biomechanics system uses multiple cameras tracking passive, reflective markers attached to the subject's body. The cameras track the subject in three dimensions, sampling the marker positions at between 30Hz and 60Hz capture rate. The information gathered is then post-processed, with one second of data taking up to one minute to process. Note that this is not a real-time system.
Interface:	RS-232C serial
Update Rate:	30 to 60 Hz capture rate (not real-time)
Range:	10' x 10' x 12' tracking volume
Accuracy:	Unavailable
Latency:	0.1 sec
Problems:	Non-real-time, shadowing, limited work area.
Cost:	Unavailable
RHBTS Cost:	N/A
Guarantee:	Unavailable
Comments:	This system is not capable of tracking an entire human body in real time. It would, however be suitable for post-production motion capture (ie. production animation applications).

Haptek

Contact:	Peter Broadwell
Address:	104 Locust Street, Suite 201, Santa Cruz, CA 95061
Phone:	(408)469-4394 [(415)325-2342]
Fax:	(408)469-4394
e-mail:	peter@meer.net
Method:	Mechanical, Exoskeletal with force-feedback
Overview:	The HAPTEK system uses an upper body exoskeletal system which senses the users upper body lean and twist, 3DOF shoulder and 1DOF elbow movement. It provides force-feedback from 0 to 80 lbs (user controlled) in response to objects the user encounters in the synthetic environment.
Interface:	Uses Macintosh 7100 Power PC for system control
Update Rate:	30 frames/sec in Haptek application Data update rate in the kHz range.
Range:	N/A -- Ground-based
Accuracy:	0.2 degree angular resolution
Latency:	0.1 msec
Problems:	User encumbrance (which is necessary for force-feedback), moving parts which suffer from wear, limited work area
Cost:	Expected cost: $20,000-$30,000
RHBTS Cost:	N/A
Guarantee:	Unknown
Comments:	The HAPTEK system would be sufficient for applications which require tracking of and force-feedback to the user's upper body. It is not suitable for tracking an entire human body for synthetic environment applications.

Image Guided Technologies, Incorporated

Contact:	Kelly Burnham
Address:	5680 Central Avenue, Suite B, Boulder, CO 80301
Phone:	(303)447-0248
Fax:	(303)447-3905
e-mail:	Unavailable
Method:	Electro-magnetic, moving transmitter, multiple stationary receivers
Overview:	The FlashPoint system uses multiple stationary electro-magnetic receivers to detect the output signal of a hand-held digitizing probe.
Interface:	RS-232C serial
Update Rate:	200 Hz
Range:	1 m (larger with optional FlashTracker)
Accuracy:	0.5 mm at 1 m
Latency:	Unavailable
Problems:	Tracks only one point, EM interference
Cost:	Unavailable
RHBTS Cost:	N/A
Guarantee:	Unavailable
Comments:	The FlashPoint system may be good for CAD object digitizing but it is not suitable for human body tracking.

Motion Analysis Corporation

Contact:	Jerry Burg
Address:	3617 Westwind Blvd., Santa Rosa, CA 95403
Phone:	(510)426-8840
Fax:	(510)426-8840
e-mail:	sales@macorp.com
Method:	Image-based
Overview:	ExpertVision HiRES uses multiple video cameras to capture the motion of a subject placed with passive markers. Complex software analyzes the video data, picks corresponding markers from the images and calculates marker position.
Interface:	PC
Update Rate:	60-240 Hz
Range:	Can cover 25' x 25' area
Accuracy:	Unavailable
Latency:	Unavailable
Problems:	Limited range, shadowing, not suitable for interactive applications
Cost:	Unavailable
RHBTS Cost:	N/A
Guarantee:	Unavailable
Comments:	ExpertVision HiRES would be good for performance capturing for production animation work or study of human body motion but it is not suitable for real time interactive applications.

Northern Digital, Incorporated

Contact:	Margaret Fraser (Andy Johnston)
Address:	403 Albert Street, Waterloo, Ontario, Canada N2L 3V2
Phone:	(519)884-5142 [(800)265-2741]
Fax:	(519)884-5184
e-mail:	margaret@ndigital.com (andy@ndigital.com)
Method:	Image-based, multiple cameras, active Infrared LED markers
Overview:	The OPTOTRAK system uses active infrared markers attached to the subjects body. Multiple cameras track the subject. The markers are sequenced by the system for individual marker identification. A maximum of 256 markers may be simultaneously tracked. An optional device allows untethered operation of the system with up to 254 markers.
Interface:	Interfaces to PC via proprietary interface card. Optional device allows interface to any SCSI-capable computer or workstation.
Update Rate:	3 DOF tracking: 1200 Hz 6 DOF tracking: 100 Hz
Range:	Many ranges overlapping from 0.8 m to 15.0 m
Accuracy:	0.15 mm and .01 degrees at 1 m
Latency:	3 msec
Problems:	Limited range, shadowing and cost
Cost:	$58,000 (one sensor, 24 markers, associated interface equipment)
RHBTS Cost:	$170,000 (three sensors, 50 markers, associated interface equipment)
Guarantee:	One year parts and labor warranty on all components except markers
Comments:	The OPTOTRAK system seems to be the leading technology in optical tracking. Based on Northern Digital's literature, OPTOTRAK is capable of tracking a full human body in real time. The authors were not able to see an operational system while writing this paper.

Phase Space

Contact:	Tracy McSheery
Address:	2901 Susan Lane, Castro Valley, CA 94546-3219
Phone:	(510)582-2897
Fax:	(510)582-1524
e-mail:	phase1@ccnet.com
Method:	Image-based, multiple cameras, active LED targets (markers)
Overview:	System uses multiple CCD cameras to triangulate up to 128 LED's placed on the user's body.
Interface:	Serial, parallel, Ethernet, SCSI-2 Supports most systems, including PC's
Update Rate:	300-500 Hz
Range:	10 m (33 ft)
Accuracy:	1 cm resolution at 10 m
Latency:	6.6 msec
Problems:	Sourced, limited range, shadowing
Cost:	$60,000 (full 6-camera system)
RHBTS Cost:	$50,000 (4-5 camera system will full support for 128 LED's)
Guarantee:	30 day money-back guarantee
Comments:	The current literature on the Phase Space system claims that their device is capable of tracking 128 independent infra-red markers in real time. The authors were not able to see an operational system while writing this paper.

Polhemus

Contact:	Thomas Jones, x234
Address:	P.O. Box 560, Colchester, VT 05446
Phone:	(802)655-3159 [(800)357-4777]
Fax:	(802)655-1439
e-mail:	Unavailable
Method:	Electro-magnetic, AC signal, stationary transmitter, multiple receivers
Overview:	The FASTRAK and ULTRATRAK systems measure position and orientation (6 DOF) of from one to sixteen receivers relative to a stationary transmitter. Receiver differentiation is accomplished by frequency multiplexing.
Interface:	RS-232C and IEEE-488
Update Rate:	120 Hz (one receiver) 30 Hz (four receivers)
Range:	10 feet (3.1 m)
Accuracy:	0.15 degree angular resolution 0.03 inch spatial resolution
Latency:	4 msec
Problems:	Sourced, tethered, limited range, metallic object interference
Cost:	$6,100 -- Basic FastTrak system with one receiver (4 maximum)
RHBTS Cost:	$32,250 -- UltraTrak 60Hz system with 16 receivers $38,250 -- UltraTrak 120Hz system with 16 receivers
Guarantee:	One year warranty on all products.
Comments:	Polhemus clearly has devices capable of tracking the entire human body in real time. They are the current leader in the field, with the largest clientelle. The one draw-back with Polhemus devices is their susceptibility to metallic object interference. This is due to their use of AC magnetic fields. Ascension Technology Corp. claims that their use of DC magnetic fields minimizes metallic object interference. The new Polhemus ULTRATRAK system is an entirely integrated system capable of tracking the entire human body (up to sixteen independent segments) in real time.

United Technologies Adaptive Optics

Contact:	Anderson Maddocks, Director of Marketing
Address:	54 CambridgePark Drive, Cambridge, MA 02140-2308
Phone:	(617)864-0201
Fax:	(617)864-1348
e-mail:	Unavailable
Method:	Image-based, multiple cameras, infrared transmitters, passive markers
Overview:	Infrared LED illuminators mounted in a ring around the lens of each camera send a flash which is reflected from passive markers attached to the object to be tracked. The system can simultaneously track from 1 to 100 markers.
Interface:	SGI, PC or Macintosh serial
Update Rate:	30 Hz / 60 Hz
Range:	30 m indoor, 8 m outdoor
Accuracy:	angular resolution: 1/30,000 camera field of view (FOV) (Specified camera FOV 7-53 degrees depending on f-stop)
Latency:	Unavailable
Problems:	Limited range, shadowing
Cost:	Unavailable
RHBTS Cost:	N/A
Guarantee:	Unavailable
Comments:	The current capabilities of AOA's body tracking device will only support post-production animation motion capture. It is not yet suitable for real-time track of the entire human body, although they are developing a device which will have real-time capabilities. The expected release date of their real-time system is in the first quarter of 1996.

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