Journal of Neuroscience Methods 180 (2009) 224–233

Contents lists available at ScienceDirect

Journal of Neuroscience Methods

journal homepage: www.elsevier.com/locate/jneumeth

Three-dimensional, automated, real-time video system for tracking limb motion in brain–machine interface studies

Ian D. Peikon[a,d], Nathan A. Fitzsimmons[b,d], Mikhail A. Lebedev[b,d], Miguel A.L. Nicolelis[a,b,c,d,e,*]

[a] Department of Biomedical Engineering, Duke University, Durham, NC 27710, USA
[b] Department of Neurobiology, Duke University, Durham, NC 27710, USA
[c] Department of Psychology and Neuroscience, Duke University, Durham, NC 27710, USA
[d] Center for Neuroengineering, Duke University, Durham, NC 27710, USA
[e] Edmond and Lily Safra International Institute of Neuroscience of Natal, Natal, Brazil

ARTICLE INFO

Article history:
Received 13 January 2009
Received in revised form 10 March 2009
Accepted 13 March 2009

Keywords:
Brain–machine interface
Video tracking
Animal movement
Animal posture
Real-time systems

ABSTRACT

Collection and analysis of limb kinematic data are essential components of the study of biological motion, including research into biomechanics, kinesiology, neurophysiology and brain–machine interfaces (BMIs). In particular, BMI research requires advanced, real-time systems capable of sampling limb kinematics with minimal contact to the subject's body. To answer this demand, we have developed an automated video tracking system for real-time tracking of multiple body parts in freely behaving primates. The system employs high-contrast markers painted on the animal's joints to continuously track the three-dimensional positions of their limbs during activity. Two-dimensional coordinates captured by each video camera are combined and converted to three-dimensional coordinates using a quadratic fitting algorithm. Real-time operation of the system is accomplished using direct memory access (DMA). The system tracks the markers at a rate of 52 frames per second (fps) in real-time and up to 100 fps if video recordings are captured to be later analyzed off-line. The system has been tested in several BMI primate experiments, in which limb position was sampled simultaneously with chronic recordings of the extracellular activity of hundreds of cortical cells. During these recordings, multiple computational models were employed to extract a series of kinematic parameters from neuronal ensemble activity in real-time. The system operated reliably under these experimental conditions and was able to compensate for marker occlusions that occurred during natural movements. We propose that this system could also be extended to applications that include other classes of biological motion.

1. Introduction

Many research studies and practical applications require tracking of biological motion in real-time. In particular, there are many applications in which it is necessary to track the motion of an animal's or human's limbs with great accuracy for long periods of time. Many different methods for tracking limb position in animals and humans have been proposed (Harris and Wertsch, 1994; Simon, 2004; Wong et al., 2007), including systems based on infrared beam arrays (Clarke et al., 1985), Doppler radar (Martin and Unwin, 1980), ultrasound (Akaka and Houck, 1980; Georgopoulos et al., 1986), accelerometers (Giansanti et al., 2005; May et al., 1996), and gyroscopes (Giansanti et al., 2005). However, motion tracking systems using video cameras (Macmillan, 1975; Uter, 1977) are currently the most common approach to achieve this demanding task.

As video-camera technology has advanced, many video tracking applications have been developed and refined (Derry and Elliott, 1997; Olivo and Thompson, 1988; Vorhees et al., 1992). Modern video-based systems can be classified into two major categories. The first class of systems relies on off-line analysis of prerecorded data (Dielenberg et al., 2006; Figueroa et al., 2003; Noldus et al., 2001). Since it is not required that such systems operate in real-time, they can implement complicated, time-intensive, computer-vision algorithms that reconstruct biological motion by extracting positions of multiple markers placed on the body or by segmenting visual scenes without markers (Blake and Isard, 1998; Hogg, 1983; Leardini et al., 2006; Ramanan et al., 2006). The second class of systems operates in real-time. The majority of such real-time systems are based on markers placed on the limbs over joints. Markers can be passive, detected as high-contrast spots in a scene (e.g., SIMI Motion System produced by SIMI Reality Motion Systems GmbH), or active, emitting light under control of the recording system (Krist et al., 1990; Macellari, 1983; Stüssi and Müller, 1990).

* Corresponding author at: Box 3209, Department of Neurobiology, Room 327E Bryan Research Building, Duke University Medical Center, 101 Research Drive, Durham, NC 27710, USA. Tel.: +1 919 684 4580; fax: +1 919 668 0734.
E-mail address: nicoleli@neuro.duke.edu (M.A.L. Nicolelis).

0165-0270/$ – see front matter
doi:10.1016/j.jneumeth.2009.03.010

Active-marker systems have an advantage because marker identity can be easily and quickly recognized. Each marker emits a signal that differs in frequency or pattern. However, these systems necessitate the usage of either wires connected to the markers, or bulky circuitry surrounding the marker emitter. This added tethering or bulk can be inconvenient to wear and may restrict or alter typical motion and behavior, especially in many animal models.

The development of a video-based system that could take advantage of markers that did not need wires or complicated electronics to operate was motivated primarily by the demands of our primate neurophysiology experiments. Since most of our experimental routine involved the development, implementation, and testing of brain–machine interfaces (BMIs) in which chronically recorded neuronal electrical activity is used to directly control external actuators in real-time (Lebedev and Nicolelis, 2006; Nicolelis, 2001, 2003), we were in need of a system that could allow recording of biological movements in real-time to achieve efficient, on-line training of computational algorithms while the subjects performed a series of voluntary movements of their limbs. In the past, our laboratory, as well as other neurophysiology laboratories (Cisek and Kalaska, 2005; Shen and Alexander, 1997; Wise et al., 1998), has trained non-human primate subjects to operate hand-held joysticks. However, in such experimental settings, many details of arm movement often remain unrecorded, as the more complex arm motion is simplified into the endpoint of a two- or three-dimensional manipulator or joystick. Moreover, the requirement to operate a joystick can mechanically constrain natural reaching and grasping movements. Commercially available video tracking systems did not suit our needs because they were either designed for off-line reconstruction of movements or required placing wires on the subject's body – something that negatively affects motor behavior in non-human primates. Additionally, the wires used in active-marker systems often introduce electrical artifacts that can compromise our sensitive electrophysiological recording equipment. To address these concerns, we designed a system capable of tracking a variety of limb movements – with or without manipulators or joysticks – in real-time. Our system is not restricted to non-human primate experiments however, and can be easily adapted for video tracking other animals and humans.

The system described here features the following characteristics: (1) real-time tracking to capture voluntary movements of both arms and/or legs; (2) reconstruction of three-dimensional marker coordinates; (3) automatic detection and correction of marker occlusions; (4) customizability for new experiments that require motion tracking; (5) wireless markers that animal subjects can easily tolerate; (6) absence of electrical noise; and (7) the capability to be interfaced to BMI hardware via analog and digital outputs.

2. Methods

2.1. System overview

Our system reliably tracks multiple markers in three dimensions utilizing images captured simultaneously by two IEEE 1394 cameras which point at the subject from different viewing angles (Fig. 1). The locations of the cameras with respect to the experimental setup do not need to be measured; a calibration procedure at the start of each session determines the transformation between 2D camera coordinates and 3D experimental setup coordinates. The parameters of this transform are calculated using still images of 27 markers with known 3D coordinates from each camera. The tracking software, applied to the video for each camera separately, utilizes a marker movement distance minimization algorithm that enables the system to reliably track the markers, from frame to frame, without user supervision. The software is written in GNU C++. It operates on a Linux platform using the libdc1394 video capture library for IEEE 1394 devices. The speed of real-time operation is increased by enabling direct memory access (DMA). The system can perform real-time tracking of multiple markers at a capture rate of 52 frames per second (fps) or off-line tracking at up to 100 fps. During the tracking sessions, the system can reacquire markers that go out of the field of view of the cameras or have become occluded due to other objects in the line of sight. The positions of the markers can be read out in real-time as rescaled analog outputs via a National Instruments Analog Output PCI card, or as digital outputs via user datagram protocol (UDP) streams.

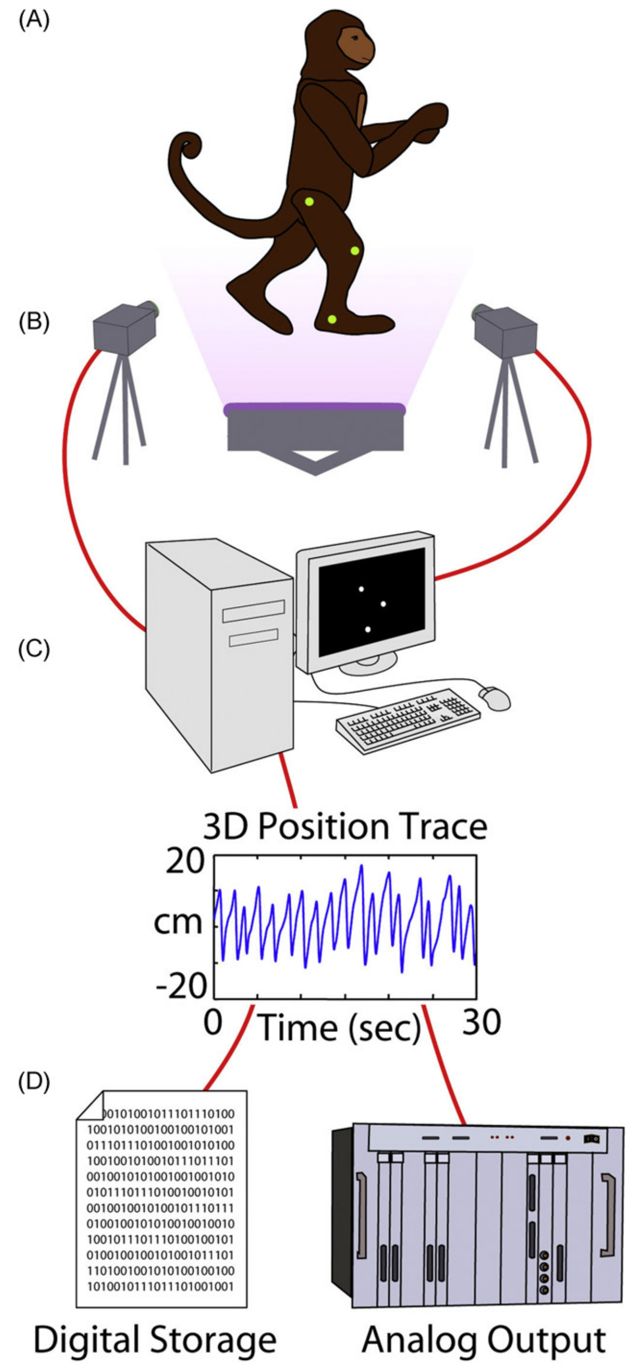

Fig. 1. Experimental setup. (A) The subject's joints are painted with fluorescent stage makeup and illuminated with a UV spotlight. (B) Firewire cameras pointed at the subject from two different angles record video at a high frame rate. (C) Computer system analyzes the frames in real-time in displays the tracking data. (D) The system outputs the tracking data in digital and analog form.