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An infrared range camera-based approach for three-dimensional locomotion tracking and pose reconstruction in a rodent

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ABSTRACT

We herein introduce an automated three-dimensional (3D) locomotion tracking and pose reconstruction system for rodents with superior robustness, rapidity, reliability, resolution, simplicity, and cost. An off-the-shelf composite infrared (IR) range camera was adopted to grab high-resolution depth images ($640 \times 480 \times 2048$ pixels at 20 Hz) in our system for automated behavior analysis. For the inherent 3D structure of the depth images, we developed a compact algorithm to reconstruct the locomotion and body behavior with superior temporal and solid spatial resolution. Since the range camera operates in the IR spectrum, interference from the visible light spectrum did not affect the tracking performance. The accuracy of our system was $98.1 \pm 3.2\%$. We also validated the system, which yielded strong correlation with automated and manual tracking. Meanwhile, the system replicates a detailed dynamic rat model in virtual space, which demonstrates the movements of the extremities of the body and locomotion in detail on varied terrain.

1. Introduction

Locomotion analyses are widely applied in neuroscience research, animal welfare, and pharmacological studies on different animal species (Tecott and Nestler, 2004), including rodents (Denenberg, 1969; Clarke et al., 1985; Pan et al., 1996; Rousseau et al., 2000; Twining et al., 2001; Spruijt and deVisser, 2006), pigs (Lind et al., 2005), insects (Noldus et al., 2001; Reynolds and Riley, 2002), arthropods (Aagaard et al., 1991), and fish (Nilsson et al., 1993; Kato et al., 1996).

Manually recording animal behavior is economical but inherently suffers from subjectivity and fatigue (Lind et al., 2005; Tort et al., 2006). Otherwise, automated locomotion recording and analysis have obvious advantages including repeatability and reliability with lower labor costs (Tecott and Nestler, 2004; Spruijt and deVisser, 2006). Early automated measuring systems were usually based on photo-cell sensors (Clarke et al., 1985; Ericson et al., 1991) or electronic touch panels (Kao et al., 1995) which are relatively more reliable than manual recording but are expensive and have low resolution (Pan et al., 1996). Since the 1980s, computer vision-based systems were introduced into the field of animal locomotion analysis (Godden and Graham, 1983), and they provided greater accuracy and flexibility than other systems (Noldus et al., 2001).

Diverse methods were presented to track animal behavior based on computer-vision, including monochrome video thresholding (Godden and Graham, 1983; Nilsson et al., 1993; Hoy et al., 1996; Kato et al., 1996; Noldus et al., 2001; Lind et al., 2005; Tort et al., 2006), color space conversion and filtering (Noldus et al., 2001; Obradovic et al., 2009), background image subtraction (Kato et al., 1996; Noldus et al., 2001; Publicover et al., 2009), and model recognition (Rousseau et al., 2000; Twining et al., 2001). Some of systems are commercially available (Spruijt and deVisser, 2006). Some efforts on three-dimensional (3D) tracking using multiple cameras (Kato et al., 1996; Fry et al., 2000) or video cameras with mirrors were presented (Chràsková et al., 1999). Three-dimensional human behavior reconstruction has been widespreaded and widely studied based on various approaches (Moeslund and Granum, 2001). Correspondingly, all sorts of three-dimensional rodent behavioral phenotyping systems were presented, HomeCageScan® (CleverSys, Reston, VA, USA) provides rodent behavior phenotyping modules based on body part feature recognition to analyze extensive rodent's behaviors, which recognize rodent behavior with video clips recorded from video cameras from limited top and side viewpoints. Otherwise, LABORAS® (Metris, Hoofddorp, the Netherlands) reconstructs rodent three-dimensional behavior with physical vibration and force signal with specific sensor instruments, which would not be affected by light intereference. But the flexibility of measurement is rather constrained and sensitive to physical noise (Spruijt and deVisser, 2006). Various qualitative validity assessment procedures were also proposed (Van de Weerd et al., 2001;

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Lind et al., 2005; Tort et al., 2006). However, applications of vision-based systems were often limited by color-related factors including contrast, brightness, animal color, complicated backgrounds, and poor tolerance to interference. Some studies further used expensive infrared (IR) cameras (Noldus et al., 2001; Lind et al., 2005; Obradovic et al., 2009).

Microsoft Kinect® (Microsoft Corporation, Redmond, WA, USA) is a low-cost (<US$ 150) commercial composite sensor device with an IR range camera, charge-coupled device (CCD) camera, microphone array, and accelerometer, and was designed for human gesture and pose recognition for the consumer market. The IR range camera and video camera composite module comes with PrimeSensor® technology (PrimeSense, Tel Aviv, Israel), which integrates IR depth images and color video acquisition in a system-on-a-chip design for high-resolution depth information registration at greater than a 30-Hz theoretical sampling rate. In this study, we developed an automatic locomotion analysis system for rats using a depth map directly acquired from the IR range camera of Kinect, which combines advantages of an IR camera and a laser range finder at a reasonable cost. Therefore, the IR range camera is capable of retrieving video in low-brightness conditions, and interprets distance (depth) information of each point in the scene as corresponding pixel values.

By interpreting depth information in the captured frames, our method is able to reconstruct continuous high-resolution 3D location and measurements of a rat, without limitations of indoor ambient light conditions, contrast, invasive labeling tags, or varying colors of the rat and background. For independence of the analysis, our system was divided into two parts: a recording part and an analysis part. The depth image recording part retrieves and compresses depth and color image streams from an IR range camera and CCD camera, respectively. The recorded depth images are device independent; any similar device which produces depth images can be used as the source for the depth image stream. The analysis part performs off-line 3D measurement reconstruction and locomotion analysis for further assessment and post hoc tests.

To validate our method, we recorded range camera frames and CCD camera frames configured horizontally. By directly accessing memory instead of using built-in functions in a computer vision library, our system achieved a sampling rate of >20 Hz with a resolution of 640 × 480 pixels.

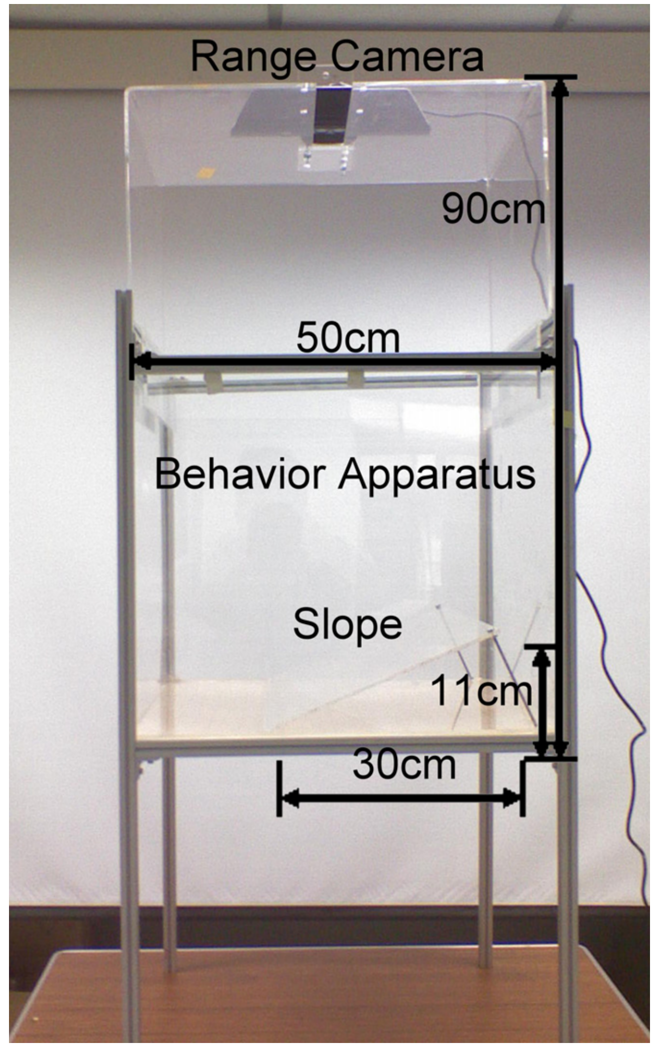

Fig. 1. Photograph of the experimental configuration including the behavior apparatus, transparent slope, and Microsoft Kinect® composite sensor. The apparatus with the transparent slope consisted of aluminum extrusions and acrylic plates for convenience of adjustment. The rat roamed freely on the floor. The Kinect® sensor was mounted 90 cm above the floor for a comprehensive view of the apparatus.

2. Materials and methods

2.1. Animals

To validate our system, 21 animals in total were used, including 5 Long Evans (378.0 g, 286.0 g, 242.5 g, 241.5 g, 241.0 g), 5 Wistar rats (386.0 g, 395.0 g, 398.0 g, 400.0 g, 417.5 g) and 5 C57BL/6 mice (34.5 g, 31.0 g, 30.5 g, 29.0 g, 27.5 g) for assessment of the effects on the system performance caused by varied fur colors and sizes of the animals. The other 2 Long Evans (285.0 g and 286.0 g), 2 Wistar rats (278.0 g and 300.0 g) and 2 C57BL/6 mice (22.5 g and 23.0 g) for lightless environment performance examination. All experimental procedures were approved by the Institutional Animal Care and Use Committee of National Ilan University, and were in accordance with guidelines specified in the "Codes for Experimental Use of Animals" of the Council of Agriculture of Taiwan, based on the Animal Protection Law of Taiwan.

2.2. Hardware

The hardware setup included a behavior apparatus, Microsoft Kinect® composite sensor device, and a personal computer. The behavior apparatus consisted of aluminum extrusions (120 cm × 52 cm × 52 cm), four acrylic side plates (50 cm × 50 cm × 0.2 cm), and an acrylic floor plate (50 cm × 50 cm × 0.5 cm) with a grid pattern consisting of 5-cm × 5-cm squares for performance validation. The sensor device was mounted 90 cm above the bottom of the apparatus to record stereo dorsal images of the rat. To assess the 3D tracking performance in a complex topographical configuration, an acrylic slope (50 cm × 30 cm × 11 cm) was set up in the behavior apparatus (Fig. 1).

The Microsoft Kinect® composite sensor device was connected to a personal computer for 3D rat locomotion and pose reconstruction (Fig. 2A). The Kinect® device acquires depth images by continuously projecting coded IR light and decodes the light reflected which contains depth information of the scene, which provides a Video Graphics Array (VGA) depth image with 3-mm spatial and 1-cm depth resolution at a rate of 30 frames/s (30 Hz) under indoor lighting conditions. Considering stablity, the sampling rate is set at a rate of 20 frames/s (20 Hz) while recording the series of depth image. Respectively, the recorded depth image series were processed by the method proposed in this paper for locomotion analysis at about 20 Hz rate. The driver for the sensor is a Code Laboratories® NUI Platform (Code Laboratories, Henderson,