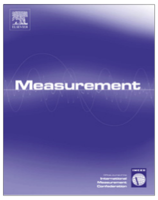
Measurement 75 (2015) 273–283

Contents lists available at ScienceDirect

Measurement

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



Concept and preliminary experiments with a wearable computer vision system for measuring shoe position and orientation[☆]

Ayron Catteau, Mojtaba Ahmadi[*]

Department of Mechanical and Aerospace Engineering, Carleton University, 1125 Colonel By Drive, Ottawa, Canada

ARTICLE INFO

Article history:
Received 2 November 2014
Received in revised form 23 July 2015
Accepted 27 July 2015
Available online 6 August 2015

Keywords:
Image processing
Pose estimation
Gait analysis

ABSTRACT

Presented in this paper is the design and prototype of a self-contained wearable system capable of measuring the relative position and orientation of the wearer's shoes. The system consists of a camera, eight LED markers, and a single board computer mounted to each shoe. The data processing is performed on-board providing a 6 DoF coordinate system transformation from one shoe to the other at a rate of 15 Hz. Using 4 healthy subjects, experiments were performed to compare this system's measurements to those of an accurate commercially available system. This system was able to correctly calculate the position and orientation between the shoes with 90% of the measurement errors being less than 7.55 cm and 16.56 deg. Overall, the experiments demonstrate that the shoe localization system is successful, but further development is required to reduce the susceptibility of the system to sources of error.

1. Introduction

Among Canadians who are over 65 years of age, falling is the cause of more than half of all reported injuries and the cause of one fifth of all injury related deaths [1]. For all Canadians, falls are the leading cause of hospitalization due to injury and the leading cause of permanent partial disability [2]. There is a multitude of research showing that balance can be improved by using a method of sensory feedback or substitution [3–8], where a metric of the subject's balance is measured and fed back to them via an alternative sense, such as touch.

The BalanceAid project was created by the Advanced Biomechatronics Locomotion (ABL) laboratory at Carleton University with the goal of creating a low-cost wearable device capable of improving the balance of the wearer. The BalanceAid project attempts to improve upon existing designs by measuring the wearer's center of pressure (CoP). In order to calculate the wearer's CoP, the BalanceAid system must measure the relative location and orientation of the wearer's shoes. In this paper, a wearable system for measuring shoe position and orientation is proposed. The proposed system is only one component of the BalanceAid project and cannot calculate the wearer's CoP on its own, only the position and orientation of the shoes. To calculate CoP, this system must be combined with a pressure sensitive insole, or a similar sensor. The system is comprised of a camera, computer, and 8 infrared LED markers attached to each shoe. Each camera captures images of the opposing shoe and calculates the position and orientation of that shoe based on the location of the markers in the image.

The system presented in this paper is the first to use two shoe mounted cameras to measure the position and

---

[☆] This research was supported by a Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant.

[*] Corresponding author. Tel.: +1 613 520 2600x4057.
E-mail address: mojtaba.ahmadi@carleton.ca (M. Ahmadi).

http://dx.doi.org/10.1016/j.measurement.2015.07.040
0263-2241/© 2015 Elsevier Ltd. All rights reserved.

orientation of the shoes during the entire gait cycle in real time and using entirely on-board processing.

In addition to balance improvement, this system could be applied to gait analysis, where there is a need for a cheap and mobile gait measurement system, or applied to pedestrian tracking, where measurement of shoe position and orientation could aid existing methods.

In 2003, Fitzpatrick and Kemp investigated the use of shoe mounted cameras for analyzing gait, obstacle detection, and context recognition [9]. They used a single camera and IMU mounted to a shoe, with image processing occurring offline. They concluded that the shoes have good potential as a location for computer vision based devices.

In 2011, Do and Suh presented a system for measuring shoe location and orientation using shoe mounted cameras and externally fixed infrared LED markers [10]. In 2012, they used a camera rigidly attached to the shoe to measure the shoe's position and orientation [11]. While walking, the camera takes images of a strip of markers fixed along the ground. Their system is able to accurately estimate the trajectory of the shoe globally, but only in a very limited setting.

The only device found that also attempts to measure the wearer's CoP using on-shoe sensors is documented in [12]. The author's device, called GaitShoe, used an array of force sensors in the sole of the shoe to measure ground reaction forces, and inertial sensors (accelerometer and gyroscopes), electric field sensors, and ultrasonic range sensors to estimate the relative location and orientation of each shoe. The electric field sensors were used to measure the height of the shoe above the ground, and the ultrasonic range sensors were used to calculate the distance between the shoes. While [12] focused mainly on gait analysis, it also contained some work on real-time sensory feedback. The GaitShoe device relies on the integration of inertial measurements and makes the assumption that the shoes move with zero vertical translation and only pitch rotation. While this is sufficient for estimating the location of the shoe while in contact with the ground, it does not provide a true three dimensional trajectory of the shoe over time.

Yuan and Chen have a system where each lower limb has an IMU to determine orientation of that limb, making it possible to determine pose and location and orientation of each foot [13]. While their system successfully tracks the wearer, including the locations of the shoes, the use of many accurate IMUs results in a costly system.

In 2013, Placer and Kovačič demonstrated a pedestrian localization system that makes use of a camera mounted on one shoe looking at a marker on the other [14]. The camera is only able to measure the position of the other shoe when the right foot is forward, and uses inertial measurements and an unscented Kalman filter (UKF) to estimate the position in between measurements. All the calculations, including image processing, were performed offline.

2. Hardware

The initial prototype of the system, shown in Fig. 1, was created using the following components:

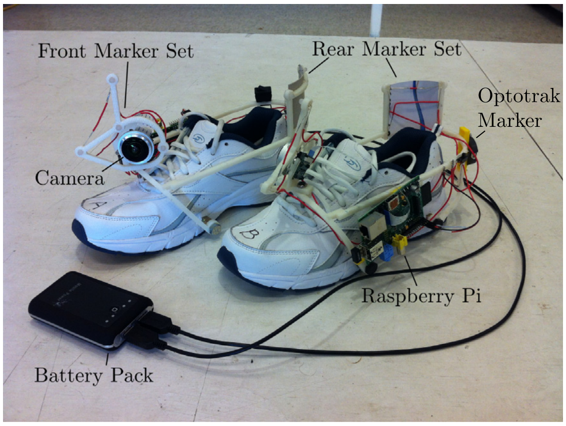


Fig. 1. Hardware assembly used in localization system.

1. The computer on each shoe is a Raspberry Pi Model B [15]. This inexpensive single board computer is capable of simple image processing, and also provides for the wireless communication via an attached 802.11g wireless USB module.
2. Each camera is composed of a Raspberry Pi NoIR camera module, a super fish eye lens from PhotoJojo [16,17], and an infrared pass filter.
3. The eight markers on each shoe are 5 mm light emitting diodes (LEDs) that emit in the near-infrared range (850 nm wavelength). The markers are grouped into two sets: the front marker set near the toe of the shoe and the rear marker set near the heal of the shoe.
4. Each structure was created using a 3D printer, and is composed of ABS plastic. The structure only contacts the shoe at four points on the shoe's sole, allowing for deformation of the upper portion of the shoe without affecting the other components.
5. A 5 V battery pack is used to power the Raspbeery Pi and LED markers. The battery pack is worn on the belt.
6. Finally, an Optotrak Certus rigid body marker is attached to the rear of the shoe. These markers are used with the Optotrak Certus, a commercial measurement system, for calibration and testing.

3. Coordinate systems

Five coordinate systems are used in this paper. Each shoe has a frame fixed to its camera, given by R for the right shoe camera and L for the left shoe camera. Each shoe also has a frame fixed to its Optotrak markers given by O_R for the right shoe and O_L for the left shoe. Lastly, there is a frame attached to the Optotrak Certus measurement tower given by T.

A transformation between two frames will be given by a $\mathbf{\Lambda}$. For example, $\mathbf{\Lambda}_{RL}$ is the transformation from R to L. $\mathbf{\Lambda}_{RL}$ is the final result of the data processing procedure, and $\mathbf{\Lambda}_{TO_R}$ and $\mathbf{\Lambda}_{TO_L}$ are measured directly by the Optotrak system. A coordinate system transformation will be represented with a translation vector and a rotation unit quaternion, for example: