*Gait Monitoring Using An Ankle-Worn Stereo Camera System*

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*Abstract*—XXX

Keywords— Gait Monitoring; Sensor Application; Computer Vision; Stereo Camera; Image Processing; Feature Extraction

# Introduction

Gait comprises of many sub phases and different parameters ~~are~~ used to accurately describe gait mechanics across these phases. The ability to measure and monitor the various gait parameters over the different phases is an important clinical tool that reveals an individual’s health status, assess whether the displayed abnormalities arise from compensation for underlying pathologies, or are causative in nature and provides reliable metrics to help with early diagnosis and intervention strategies for conditions such as Cerebral Palsy and Parkinson’s Disease. ~~Many diseases are directly related to gait. For example, neurological diseases such as multiple sclerosis, which is the most common nontraumatic cause of disability in young adults [11], or Parkinson's disease, which suffers ranges from a reduced gait speed and smaller stride length to freezing of gait [12] and has a risk increasing with age. (b) systemic diseases such as cardiopathies in which gait is affected [10]. (c) Other post-disease effects, such as stroke disability, lead to the problem of maintaining body position and walking [13].~~ However, gait monitoring in clinical or laboratory settings is an expensive and time-consuming process that requires specialized equipment, training, and examination routines. ~~Less objective caused of experts’ direct analysis of gait quality and lack of gait data.~~ With advancements in technology, it is possible to develop low-cost portable systems to supplement existing methods, while allowing for a precision and data-driven gait monitoring approach to assist in clinical analysis.

Many systems such as optical motion capture systems, inertial measurement units (IMUs), pressure walkways, and walkways with photoelectric cell bars are used to capture gait parameters and their variations in a clinical setting. ~~Commercial Inertial Measurement Units (IMU, consisting of accelerometers, gyroscopes, and magnetometers) are applied in gait monitor and analysis systems to extract spatial and temporal gait parameters to assess the mild affect gait of patients with PD or fatigue detection [1][2]~~. These systems are prohibitively expensive, have appreciable hardware complexity, and are often not user friendly. Optical Motion Capture systems require the use of body markers, data storage systems, and complex algorithms to analyze gait. It is also difficult to capture the gait width and height with this method [6]. Similarly, IMU’s can provide only gait length and not the width and height. ~~However, these IMU devices are costly, only able to detect gait length, and the precision is affected by the anatomical placement site [\*1]~~. Floor sensing products, such as pressure measurement mats [3] or walkways with photoelectric cell bars [4], are quite limited in their spatial and temporal resolutions and are cumbersome to setup. ~~can also identify gait dysfunction and quantify kinematic data for treatment analysis through parameters like gait lengths. Nevertheless, a well-designed laboratory environment restricts the performance of such a method. Meanwhile, the narrow and short pathway limits patients' mobilities. Current research extract gait parameters through video sequences with machine learning and image processing [5].~~ ~~A gait analysis method uses two sagittal plane view cameras and OpenPose that achieves a satisfactory average step length error compared with 3D motion capture [6]. But it needs manually fix the mismatch person and key points during OpenPose detection and requires participants to walk perpendicularly at a fixed depth relative to the camera. Therefore, gait width and heights are left out in the measurement.~~



Figure 1. A 3D rendering image shows the whole idea: people walking on pathway with devices, cameras on the device shooting images, show gait XYZ position(indicate capable to measure)

~~In summary, current gait monitoring devices face the following challenges. First, measurement devices are expensive and restricted to specific environments. Therefore, it is hard to install and implement. Second, device measuring needs considerable computing power with advanced GPUs. Furthermore, extra hands-on engineering is required for doctors and nurses. Last, devices cannot extract major spatial gait parameters: gait length, width, and height. There is still room for improving accuracy.~~

Here, we propose a new method for measuring the gait parameters, that can allow practitioners to supplement their existing measurement setups in a convenient manner, and demonstrate a prototype. The system comprises of an ankle wearable that contains a NIR camera system, Force Sensing Resistors (FSR), on-system markers for capture, and a Raspberry Pi board. The system is low cost, suitable for rapid prototyping and real-life measurement, easy to use, is battery operated, and provides competitive accuracy. The main contributions are as follows.

* ~~Incorporation of computer vision to the traditional wearable gait monitoring system~~.
* Application of ArUco marker and stereo camera system to extract gait length, width, and height.
* Privacy protection (Advantage of using infrared images and low-resolution images)

# System Overview

## Hardware Design

Figure 2. shows a picture of the complete system and an outline of its operation. There are two wearables in the system, one for each ankle. Each wearable is outfitted with a Pi Zero 2W, two NoIR V2 cameras that have a 780nm infrared filter, and portable batteries to form a stereo camera. The Pi has a 1GHz Quad-Core Processor with 512MB LPDDR2 RAM [7] and runs on the Pi OS. The signal from the FSR is used to trigger the cameras to take images of the marker on the other bracelet during the toe-off and heel strike phases. ~~The NoIR cameras are similar to the cameras on smartphones except without infrared filters.~~ Its NoIR illumination wavelength varies from 350 to 800nm [8]. Therefore, with the 780nm InfraRed filter, the image presents scenes under 780 to 800nm light~~. Compared with the visible wavelength camera images (380 to 700nm),~~ While the infrared cameras are unable to resolve fine details, they can easily resolve details with high contrast, such as the markers, thus affording an element of privacy in the data capture. A 1200mAh Pisugar3 provides 8-10 hours of battery life. Depending on the patients' conditions and needs, a small volume of 3.7V Lithium-ion Polymer Battery can support reduced dimension and comforter devices.

 

*Figure 2. a) Demonstration of devices: UART, pi connection, circuit, FSR, camera, filter; b) flow chart; c) pseudo-code*

The FSR used is a 0.5-inch circle polymer thick film sensor that exhibits a decrease in resistance with an increasing force applied to the sensor's surface. Two FSRs are placed under the shoe, one at the first metatarsal and the other under the heel [9]. The FSR circuit is a simple voltage divider. The approximate time required for a repeatedly discharged capacitor to reach its high state is determined by the size of the FSR impedance and roughly indicates the force on the FSR. A trigger signal will be sent to the Raspberry Pi once it is below the threshold. The transfer of the pixel position of the marker between Pis on the same bracelet, and ensuring both cameras take images simultaneously when steps occur, goes through on UART. To make the bracelet model fit most people, the 3D printed model can slightly deform to install on the ankle with velcro tape. The dimension of the whole device is XXX, XXX, XXX. And the weight is XXX.

## Image Processing and Stereo Camera

Each image first does the feature extraction to get the marker position and then combines it with data from another camera to calculate the 3-axis gait parameters.

The 3.3 x 3.3 cm ArUco markers from the default dictionary are applied to feature extraction. Images containing markers will be transferred to binary images that are detectable. Pixel values greater than the threshold are assigned to 1 and 0 otherwise. Since the infrared image contains limited visual details, using a global value as a threshold for the binary image will eliminate part of the marker information and make it harder to detect. Hence, every pixel has its threshold estimated through a small pixel region around it. The threshold value can be the mean of a small neighborhood area of a pixel or a weighted sum of KernelSize x KernelSize neighbor area of a pixel minus an offset, where the weighted sum is a cross-correlation between the neighbor area and the same size Gaussian window. The 1D Gaussian kernel can be obtained through:

where , and is scale factor so that . Default sigma is from standard deviation. 2D Gaussian kernel is the product of two 1D Gaussian functions. XXX (explain when to use each method, Gaussian reduces some noise).

Diagram

Description automatically generatedA close-up of a person's shoe

Description automatically generated with low confidenceGraphical user interface

Description automatically generated

*Figure 3. a) Principal demonstration of Aruco and Stereo Camera, will redraw and put marker, camera signs, planes on it; b) Image processing effect (Using Mean) c) Marker Detection in IR image, redo for 720p image*

A binocular stereo camera is an approach for estimating the depth of 3D structure from two images. A scene in world coordinates can be transformed to camera coordinates, then perspective projected to the image plane. The mapping between the image plane and the image sensor can be described as the camera's intrinsic parameters, representing the camera's internal geometry. An orthonormal orientation ()/rotation () matrix shifts a 3D point to the camera frame. However, the equations for perspective projection are non-linear. Therefore, it is often convenient to express both intrinsic and extrinsic matrices as linear equations through Homogeneous coordinates, as shown in (1) and (2), respectively:

where and are the object positions on the image plane, camera, world coordinate, and Homogeneous coordinates, are the focal lengths in pixels in the x and y directions, and principle point where the optical axis pierces the sensor, are the vector value from .

Combining the above two equations, we get the full projection matrix that maps 3D points to 2D image pixels, which 'mathematical represents' the camera.

The 3x4 projection matrix requires the knowledge of intrinsic () and extrinsic () parameters of the cameras being used. A one-time calibration procedure is needed to solve . The calibration code captures an image of an object with known geometry (e.g. chessboard), then identifies the correspondence between 3D scene points and the captured image. Each pair of correspondence provide 2 independent linear equations. Since there are 11 unknowns in , at least 6 pairs are mandatory. In the last, from , we can solve for and .

Given a calibrated camera, projection of an image point back into the scene results in outgoing rays as shown in Figure 3(a). With a second camera, we can backward projection to find 3D scene points.

# Result and Discussion

 

*Figure 4. a) picture of device on body, demonstrates our definition of gait length, width, and heights; b) Experiment setting*

## Experiment Setup

As shown in Figure 4a, gait length and width is a vertical and horizontal distance between the point of initial contact of one foot and the point of initial contact of the opposite foot along the walking direction. Gait height is the height of the ankle during the norm flatten feet period.

We measure the gait length, width, and height over 30 steps from 3 participants. First, participants are asked to walk without devices. Then each step is marked on the ground to get the parameters' ground truth. Later, participant repeats their gait pattern through the previous track with devices.

## Result

|  | Accuracy | Average error for one step | Error Rate for one step |
| --- | --- | --- | --- |
| Gait Length |  |  |  |
| Gait Width |  |  |  |
| Gait Heights |  |  |  |

Discussion about the result. XXX

## ~~Privacy Protection~~

~~1. Infrared image indoor (low infrared light source) blur; 2. Outdoor (Loss detail, poor visual effect, missing color information); 3. The expected places is in hospital, public place, so privacy is not critical.~~

# Conclusion

XXX

##### Acknowledgment *(Heading 5)*

This work was mainly supported by Hongrui Jiang's Lynn H. Matthias Professorship. The computer vision algorithm utilized in this work was separately developed under a grant by the National Institute of Biomedical Imaging and Bioengineering of the U.S. National Institutes of Health (award number R01EB019460). The authors thank Dr. H. Liu for technical discussions.

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