Demo: IMU-Kinect: A Motion Sensor-based Gait Monitoring System for Intelligent Healthcare

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ABSTRACT

Gait rehabilitation is a common method of postoperative recovery after the user sustains an injury or disability. However, traditional gait rehabilitations are usually performed under the supervision of rehabilitation specialists, meaning the patients can not receive adequate care continuously. In this paper, we propose IMU-Kinect, a novel system to remotely and continuously monitor the gait rehabilitation via the wearable kit. This system consists of a wearable hardware platform and a user-friendly software application. The hardware platform is composed of four Inertial Measurement Units (IMU), which are attached on the shanks and thighs of the human body. The software application is able to estimate the rotation and displacement of these sensors, then reconstruct the gait movements and calculate the gait parameters according to the geometric model of human lower limbs. Based on IMU-Kinect system, the users of gait rehabilitation just need to walk normally by wearing the IMU-Kinect kit, and then the rehabilitation specialists can analyze the status of postoperative recovery by remotely viewing the animations about users' gait movements and charts of the general gait parameters. Extend experiments in real environment show that our system can efficiently track the gait movements with 9% rotation and displacement error.

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CCS CONCEPTS

• **Human-centered computing** → *Ubiquitous and mobile computing systems and tools.*

KEYWORDS

Wearable computing; Gait monitoring; Intelligent healthcare

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1 INTRODUCTION

Gait rehabilitation is a common method of postoperative recovery, which assists the patients to learn how to walk after sustaining an injury or disability. Traditionally, gait rehabilitations are performed under the supervision of rehabilitation specialists, because the incorrect action may cause secondary damage. However, due to the lack of human resources from rehabilitation specialists, the patients usually can not receive adequate care continuously for gait rehabilitation. Therefore, an intelligent system for remote monitoring is in great demand, which allows the patients to rehabilitate at anytime and anywhere, and simultaneously allows the specialists to remotely observe their actions and assess their exercises.

Existing gait monitoring systems usually have some drawbacks when they are used for gait rehabilitation at home. Computer vision-based solutions in [2] and [6] can directly track the movements of lower limbs, but it is difficult to calculate gait parameters efficiently because such calculations require high performance devices and training data. Other solutions are mainly based on wearable sensors reported in [8], such as pressure sensors and shoe sensors in [7]. The gait parameters can be easily extracted from measurements of wearable sensors, but we can't obtain the changing trace of lower limbs because these sensors only provide patchy measurements.

In this demo, we propose IMU-Kinect, a novel system to remotely monitor the gait rehabilitation. Different from previous works, IMU-Kinect can not only track the movements of lower limbs, but also can estimate the gait parameters. The basic idea is that we can estimate the rotation and displacement of thighs and shanks based on the Inertial Measurement Units (IMU) attached on the lower limbs, because the motion data of these IMUs are consistent with the corresponding body movements. From the motion data, we can detect the gait phases and divide the gait periods. By combining the motion data with geometric models of human lower limbs, we can estimate the gait parameters.

2 SYSTEM DESIGN

System Overview

Figure 1 shows the main functional components of the IMU-Kinect system: 1): *Perception Module* is used for collecting the inertial data including gyroscope and accelerometer data, and then transferring them to the cloud server; 2): *Gait Analysis Module* extracts the motion data from the original inertial data and then estimates gait parameters; 3): *Display Module* displays the gait movement and gait parameters to specialists.

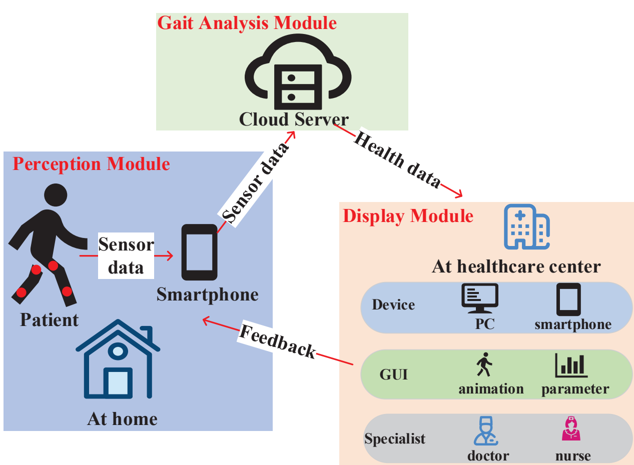


Figure 1: System Architecture.

Perception Module

We use the perception module to collect the motion data from the patients during the gait rehabilitation training. The perception module consists of a low cost wearable kit and a smartphone. The wearable kit is composed of a MicroController Unit (MCU), four Inertial Measurement Units (IMUs), a bluetooth agent and a power bank, as shown in Figure 2,

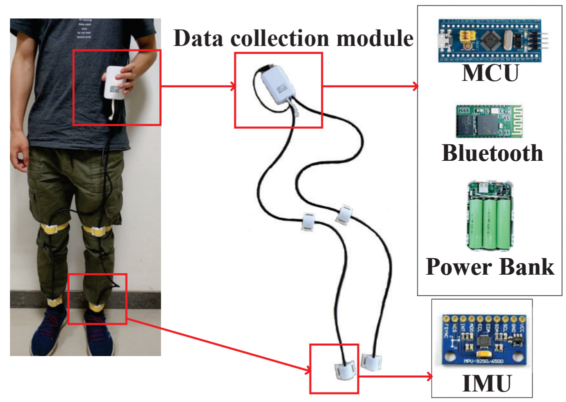


Figure 2: IMU-Kinect Kit & Deployment.

which is easy to wear. The IMUs are deployed on the thighs and shanks of the two legs with straps, which are used to measure the motion data, including the acceleration and angular velocity. In our demo, we deploy the IMUs above the ankles and above the knees as shown in Figure 2 because the sensors can be stably fixed around these positions. The MCU reads sensor data via iic bus and forwards these data to the paired smartphone via bluetooth. By wired data sampling, the efficiency of data reading is guaranteed and the conflict of wireless channels is avoided. MCU samples these four IMUs in turn in each loop, so we can believe that the sensors are synchronous. We use power bank to power the entire system and it's portable and rechargeable. The fully charged system can work continuously for five hours. The total cost of the module is below 50$ and it is affordable for a normal family. The smartphone transfers the sensing data to the cloud server via cellular network or wifi after each training. Benefited from the portability of this architecture, the users can perform gait training freely without activity range limitations.

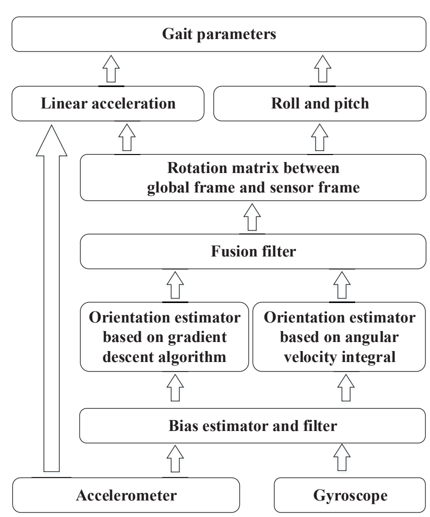


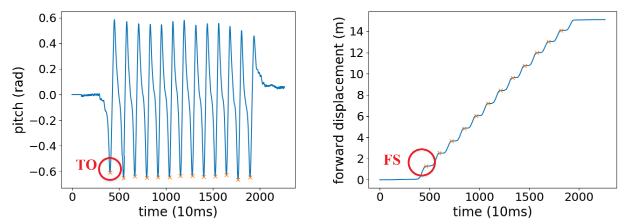
Figure 3: System Workflow.

Gait Analysis Module

The gait analysis module is designed to analyze the motion of IMUs and estimate the gait parameters. Figure 3 shows the main process of the gait analysis module. Firstly, we analyze the motion of each IMU including the rotation and displacement. Then we combine motion data from multiple sensors to calculate the gait parameters.

Motion Analysis. The motion analysis focuses on the rotation and displacement estimation. For each IMU sensor, the accelerometer measures sensor's acceleration mixed with the gravity acceleration. When the sensor is stationary, the accelerometer measures the amplitude and direction of the gravity in the sensor frame. From the gravity vector observations, we can estimate the rotation matrix between global frame and sensor frame. Because of the sensor movement, the rotation matrix calculated from accelerometer is full of high-frequency noise. The gyroscope measures the angular velocity. If we know the initial rotation matrix relative to the global frame, we can integrate angular velocity over time to update the sensor's rotation matrix. Due to the drift in gyroscope measurements, the integration of angular velocity will lead to cumulative error in the calculated rotation matrix. We calculate the rotation matrix based on the fusion filter in [4] to avoid high-frequency noise and cumulative error. Then we can extract the roll and pitch angles from the rotation matrix. And based on the rotation matrix, we also remove the gravity acceleration component from the acceleration to get linear acceleration. Because of the calculation error in linear acceleration, double integration of linear acceleration will lead to huge error. To solve the problem, we detect the gait cycle and break up the time series according to these gait break points. Traditionally, the velocity of sensor can be regarded as zero at these break points. Thus, we can estimate the displacement in each segment by the segmented double integration. Finally, the complete displacement is calculated by accumulating the displacement of each segment.

Gait Parameters Estimation. The gait parameters estimation is based on the motion data from multiple sensors of the IMUs. Gait parameters usually consist of the temporal parameters and spatial parameters [3]. The temporal parameters mainly include swing time, stance time and stride time. The spatial parameters mainly include step length, stride length and stride width. We use the motion data from IMUs attached on the ankles to estimate the temporal parameters. In order to estimate the gait parameters, we separate each stride into several gait phases and leverage the gait phase for parameter estimation. The gait phases are defined by consecutive occurrences of foot strike (FS), flat foot (FF), heel off (HO) and toe off (TO) [5]. In this demo, we identify each stride by detecting the TO events and the TO events, which correspond to the moments when the trace of pitch angle is at the valley, as shown in Figure 4(a). The stride time is calculated from the time interval between the adjacent TO events. We use the displacement of sensor to detect the FS events. We find the displacement is stationary when the feet land on the ground. Thus, the FS events can be detected by finding the stationary points in the forward-direction displacement. The swing time is the time interval between the TO event and FS event. And stance time is time difference between the stride time and the swing time. The spatial parameters are calculated based on the Denavit-Hartenberg transformation [9]. Based on the pitch and roll of shanks and thighs as well as the length of lower limbs, we can calculate the position of feet in the human body coordinate system shown in Figure 5. The step length is the distance projection between two feet on the longitudinal axis at the moment of TO, and the stride width is the projection on the lateral axis [3]. The stride length is the sum of two consecutive step lengths.



(a) TO Detection (b) FS Detection

Figure 4: Gait Segmentation

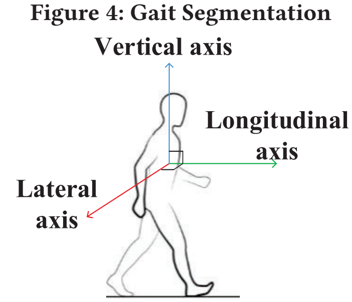


Figure 5: Human Body Coordinate System.

Display Module

We implemented the display module to provide the user-friendly interface for the rehabilitation specialists, so that they can assess the gait movements of patients. As shown in Figure 6, we provide the skeleton animations and gait parameters for the specialists in the display module. The animations reconstruct the gait movements of both the thighs and shanks based on the rotations and displacements of IMUs. From the animations, the specialists can directly observe the abnormalities of patients' gait and analyze the recovery status based on the gait movements. Besides, we also provide the charts of dynamic gait parameters and dashboards of gait parameter values, which are synchronized with the animations. From the charts and dashboards, the specialists can clearly access the statistics of gait parameters. Thus, they can compare these statistics with normal indicators to evaluate the rehabilitation. Based on the display module, the rehabilitation specialists can easily monitor patients' gait movements remotely.

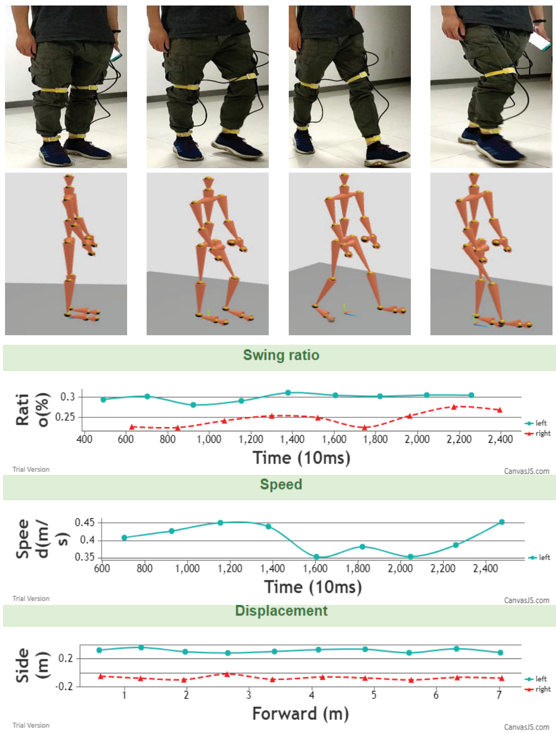


Figure 6: IMU-Kinect System.

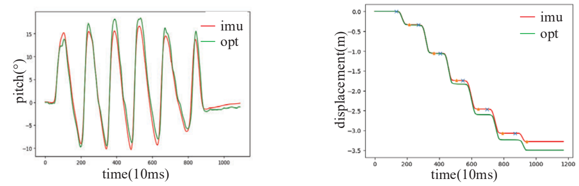
3 IMPLEMENTATION

Hardware. IMU-Kinect hardware consists of a wearable kit, a smartphone and a laptop. The wearable kit includes four MPU9250 IMUs, a STM32F103C8 MCU, a bluetooth module and a power bank. The sampling rate of IMUs is set to 100Hz. The smartphone adopts the Android 6.0 system and the laptop adopts Windows 10 system.

Software. The IMU-Kinect kit is developed on arduino platform, the gait analysis system is developed in Python and Java and the display module is developed in HTML5 and JavaScript. Our animations references the implementation of [1]. We deploy the system on a Dell Inspiron7472 laptop, equipped with 1.8 GHz and 8 G memory.

4 PERFORMANCE EVALUATION

We use the Optitrack system to capture the ground truth to evaluate our system. We attached markers on the surfaces of sensors and calculate sensors' movements by our system and Optitrack system, respectively. As shown in Figure 7, our results are very close to the ground truth. The results of repeated experiments show that experiments show that the average error in rotation angles is below 5° and average error in displacement of each step is below 7cm. And our estimated parameters are consistent with specialists eye observations.



(a) Rotation (b) Displacement

Figure 7: Evaluations

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