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A Smart Shoe for building a real-time 3D map☆

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ABSTRACT

Three dimensional (3D) mapping of environments has gained tremendous attention, from academic to industry to military, owing to the ever increasing needs of environmental modeling as well as monitoring. While many highly effective techniques have been reported thus far, a few even turned into commercial products, none has explored the use of wearable sensors to capture human foot motion, gait, and phase for 3D map construction, especially in the Architecture, Engineering, and Construction (AEC) domain. In this work, we propose a smart (and wearable) shoe, called "Smart Shoe", which integrates multiple laser scanners and an inertial measurement unit (IMU) to build a 3D map of environments in real time. Such a Smart Shoe can be a potential tool for floor plan surveying, construction process monitoring, planning renovations, space usage planning, managing building maintenance and other tasks in the AEC domain. Besides, this Smart Shoe could assist disabled people (blind people) to navigate and avoid obstacles in the unknown environment. In another case, the shoes may help firefighters quickly model and recognize objects in the firing, dark, and smoky buildings where traditional camera-based approaches might not be applicable. We integrate this shoe with a novel foot localization algorithm that produces a smooth and accurate pose and trajectory of human walking, which is the key enabling technique to minimize data registration errors from laser point cloud.

1. Introduction

Three dimensional (3D) mapping of an unknown environment is open and important research since it has broad applications in environmental searching, automation in construction, exploring and monitoring [1,2]. Laser scanners can be used to collect 2D measurements of a facility's as-built condition, and the resulting point cloud can be processed to construct a 3D map for the Building Information Models (BIMs) [3]. There are successful research efforts in this field, and some of which have been turned into commercial products such as Velodyne LiDar [4]. Integration of laser scanners or 3D LiDar sensor to build a 3D map of the environment is reported in [5–8]. Their proposed 3D mapping systems integrated on a mobile vehicle can work in large scale environments, but they are not appropriate to a normally worm device such as the Smart Shoe in this paper. Due to natural localization challenges [9–11,4] of human foot motion based wearable sensors, not much research on 3D real-time mapping wearable sensor devices on the foot has been reported yet.

The original idea for this paper started from our observation of human foot motion gait of which we can exploit to design a Smart Shoe which is a compact wearable device. This Smart Shoe with 3D real-time mapping abilities has potential applications such as: helping visually impaired users improve their capabilities of navigation and movement; or helping firefighters quickly model and recognize objects in the fire and dark smoky buildings where cameras may not be useful.

In the Architecture, Engineering, and Construction (AEC) domain, the Smart Shoe can be used for floor plan surveying, construction process monitoring, planning renovations, space usage planning, managing building maintenance. Since the Smart Shoe is lightweight and works in real-time it can be used as a construction safety monitoring and training tool.

This Smart Shoe implementation with wearable sensors including laser scanners and an inertial measurement unit (IMU) faced several challenges. First, it requires a very compact design for the natural movement of feet, such as: fast walking, climbing up or down, running or jumping. Second, the accuracy of tracking position and orientation of foot motion is crucial in building a 3D map [12,13]. Finally, because the swing of laser scanners during foot motion definitely increases the noise of collected data, it obviously reduces the accuracy of 3D map result.

In order to deal with these challenges, we utilized the human foot motion gait to implement a human foot motion localization algorithm for accurate and smooth foot motion position, and to swing laser scanners how they could scan a full 3D mapping of environments. The results of this proposed Smart Shoe could be a frame work for other potential researches and applications of mobile wearable devices for

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3D mapping in real-time. The initial report of this work has been presented in [14].

The remainder of the paper is organized as follows. The next section presents an overview of the Smart Shoe design, and data collection and processing. Section 3 presents a real-time human foot motion localization scheme. The 3D mapping algorithm for the Smart Shoe is presented in Section 4. Section 5 presents experimental results to demonstrate the effectiveness of the proposed Smart Shoe. Finally, an extended discussion of possible applications of the Smart Shoe in ACE and future work concludes the paper in the conclusion section, Section 6.

2. Overall Design of a Smart Shoe

In order to help reader be insightful the methodology of this Smart Shoe and how it could exploit gait phases of human foot motion to build a 3D map of environments, this section shows an overview of the proposed Smart Shoe design and how this design guarantees for successfully building a 3D map.

2.1. Design of a Smart Shoe

The Smart Shoe sketch and its components are depicted in Figs. 1 and 2, respectively. There is one IMU sensor mounted on the front top of the shoe to help localize the foot during walking. Additionally, two 2D laser range scanners are mounted on the front and rear of the shoe to scan the surrounding environment. Data from these IMU and laser range scanners are transferred to laptop computer for real-time data processing. Both real-time human foot localization and 3D mapping algorithms (Fig. 2) run in the computer to create a 3D map of the surrounding environment during the foot motion.

Mounting the laser range scanners on the shoe/foot has several advantages comparing to mounting on other body parts. First, by utilizing the foot motion during the walk, a 3D scanning field can be created without using other supporting actuation mechanisms such as motors to rotate the laser scanners, and this can help save energy/power. Likewise, mounting on the wearer's chest, back, or head leads to a need of an actuator to rotate the laser scanner in order to have a 3D scanning field. Second, the foot motion has two different phases, stance and swing, as shown in Fig. 3 which can be utilized to reduce IMU drift to enhance the accuracy of the foot localization. The higher accuracy of foot localization, the better accuracy of the 3D map. Third, it is more convenient and easier to mount laser scanners on the shoe than on other body parts.

In this design (Fig. 1), the *SmartShoe* frame is considered as a rigid body frame [15] which includes three sub-body frames: *Laser Scanner*1 on the front of the shoe, *IMU* under the front laser scanner, and *Laser Scanner* 2 on the rear of the shoe. The distance between the two centers, O_1 of the *Laser Scanner* 1 frame and O_2 of the *Laser Scanner* 2 frame, is $d_{O_1O_2}$, and an axis O_1O_2 is parallel to the ground. Because the body frame of the Laser Scanner 1 is setup to be the same as the Smart Shoe frame, O_1 is equivalent to O_S of the Smart Shoe frame.

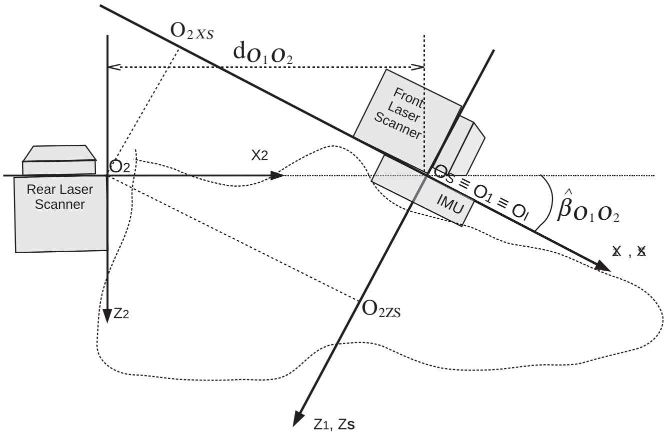

Fig. 1. The Smart Shoe design.

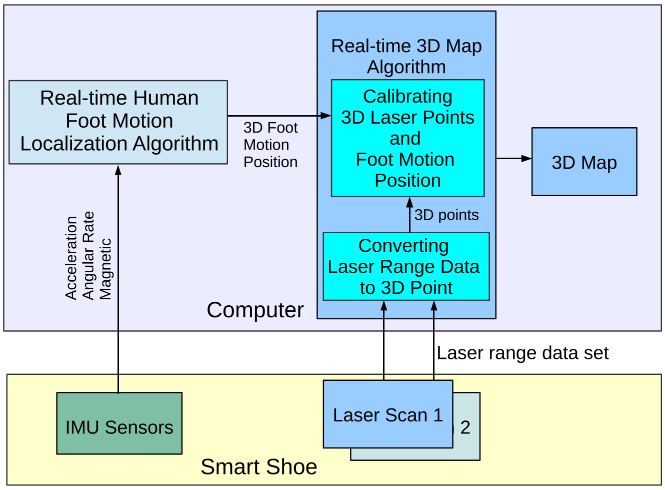

Fig. 2. The Smart Shoe's Components.

Likewise, the *IMU* frame is also equivalent to the Smart Shoe frame, hence the original center O_I of *IMU* frame, O_S of Smart Shoe frame, and O_1 of Laser Scanner 1 frame are equivalent, or $O_S \equiv O_1 \equiv O_I$, as shown in Fig. 1. This leads to the angle rate of *IMU* (*Roll*, *Pitch*, *Yaw*) during foot movement be also the angle rate of Laser Scanner 1 and Smart Shoe frames, respectively.

Since two laser range scanners are mounted on different positions, they have different detected/scanned areas, detected distances, number of points per scanning, and scanning frequencies. In this design, because the coordinate systems of Smart Shoe and Laser Scanner 1 are setup equivalently to *IMU* coordinate system, their Z axis is pointing toward the ground as shown in Fig. 1. Also, X_1, X_I and X_S are equivalent to the *Roll* axis; Y_1, Y_I and Y_S are equivalent to the *Pitch* axis; and finally Z_1, Z_I and Z_S are equivalent to the *Yaw* axis.

2.2. Scanning field of the Smart Shoe

Because a crucial requirement for this Smart Shoe to successfully build a 3D map is its capability of helping laser scanners scan fully 3D sphere space above the ground, missing any portion of this space can lead to the failure of building a full 3D map of environments. When observing gait phases of human foot motion (see Fig. 3), we discovered that the changing angle of foot motion could help the front and rear laser scanners scan a maximum angle of $5\pi/6$ around the *Pitch* axis. This maximum angle, of course, depends on walking speeds [16,17]. Hence, by integrating two laser range scanners on the rear and front of a shoe, the scanning field can reach to a maximum covered angle $5\pi/6$ such as in Fig. 4.

In Fig. 4, the yellow and green major sectors are the detected areas of the Laser Scanner 2 and the Laser Scanner 1, respectively. The 3D space volume covered by the yellow and green color areas is the scanning field of the Smart Shoe moving from the stance phase to the swing phase in one step. Furthermore, the gait and positions of this movement can be divided into two phases and 8 positions [16,17] as shown in Fig. 3. The maximum scanning angle of Laser Scanner 1, $\hat{\gamma}_1^{1,6}$, and Laser Scanner 2, $\hat{\gamma}_2^{1,6}$, can be estimated at positions 1 and 6 of the human gait phase in Figs. 3 and 4. Therefore, a total physical scanning angle composed by both Laser Scanners 1 and Laser Scanner 2 is obtained as followed:

$$\hat{\gamma}_{1U}^{1,6} = \hat{\gamma}_1^{1,6} - \hat{\gamma}_{1L}^{1,6} \tag{1a}$$

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