

Error Correction for Foot Clearance in Real-Time Measurement

Y. Wahab¹, N. A. Bakar, M. Mazalan

Advanced Multidisciplinary MEMS Based Integrated Electronic NCER Centre of Excellence (AMBIENCE),
School of Microelectronic Engineering,
Universiti Malaysia Perlis (UniMAP),
02000 Kuala Perlis, Perlis, Malaysia

E-mail: yufridin@unimap.edu.my

Abstract. Mobility performance level, fall related injuries, unrevealed disease and aging stage can be detected through examination of gait pattern. The gait pattern is normally directly related to the lower limb performance condition in addition to other significant factors. For that reason, the foot is the most important part for gait analysis in-situ measurement system and thus directly affects the gait pattern. This paper reviews the development of ultrasonic system with error correction using inertial measurement unit for gait analysis in real life measurement of foot clearance. This paper begins with the related literature where the necessity of measurement is introduced. Follow by the methodology section, problem and solution. Next, this paper explains the experimental setup for the error correction using the proposed instrumentation, results and discussion. Finally, this paper shares the planned future works.

1. Introduction

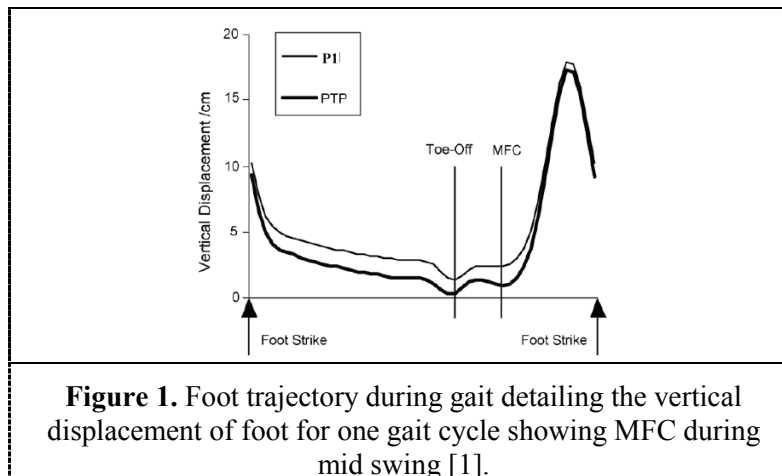
Due to the large incidence of fall among the elderly populations, the healthcare cost are increasing globally especially due to gait related injuries. As higher percentage of the world population, including Australia, is made up of the elderly, more incidents of elderly related fall injuries is expected each year. In Australia, the fall related injuries consume about \$3 billion as reported in 1999 [1]. Foot clearance is an important gait parameter that directly influences the risk of fall among the elderly. The distance of shoe sole above the ground is represented by foot clearance which is the vertical spatial parameter of the foot during the swing phase of the gait cycle. In a recent analysis study of the tripping and falls risks among the elderly individuals during walking [1,2,3], it is reported that the most critical event that can initiate the possibility of trip-related fall is the movement of the foot during mid-swing phase. This atmospherically critical parameter is called minimum foot clearance (MFC). The pattern of foot clearance during gait is depicted in Figure 1 where MFC of below 5 cm and foot trajectory of up to about 17 cm is shown [2].

To date, gait analysis study is still mostly performed in a specially set-up motion analysis laboratory using high-end motion imaging systems. In another measurement set-up, the analysis requires a

¹ To whom any correspondence should be addressed.



physician to observe visually the gait. These two approaches are undoubtedly expensive [4]. Despite the current practices, the reality proves that the demand for real life portable measurement and monitoring devices are raising fast. For that reason, a portable motion detector shoe is developed with ultrasonic and inertial measurement unit combined together to perform better in real life environment to allow comprehensive analysis and intensive monitoring. In situ measurement where the actual activities and measurement are performed such as reported in [5] reduces cost as the time requiring the presence of physician is reduced in addition to the cheaper device cost demanded. Potential of ultrasonic and its modelling for this specific application have been reported before [6,7,8].

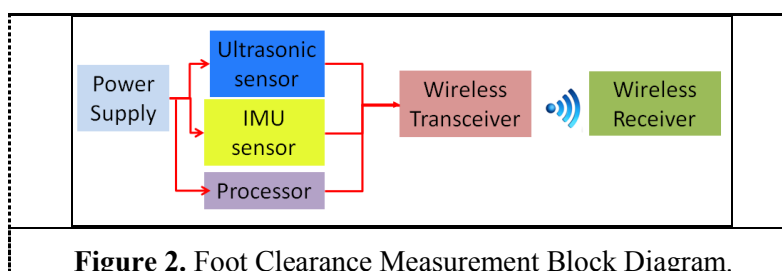


2. Methodology

2.1. Ultrasonic Distance Measurement

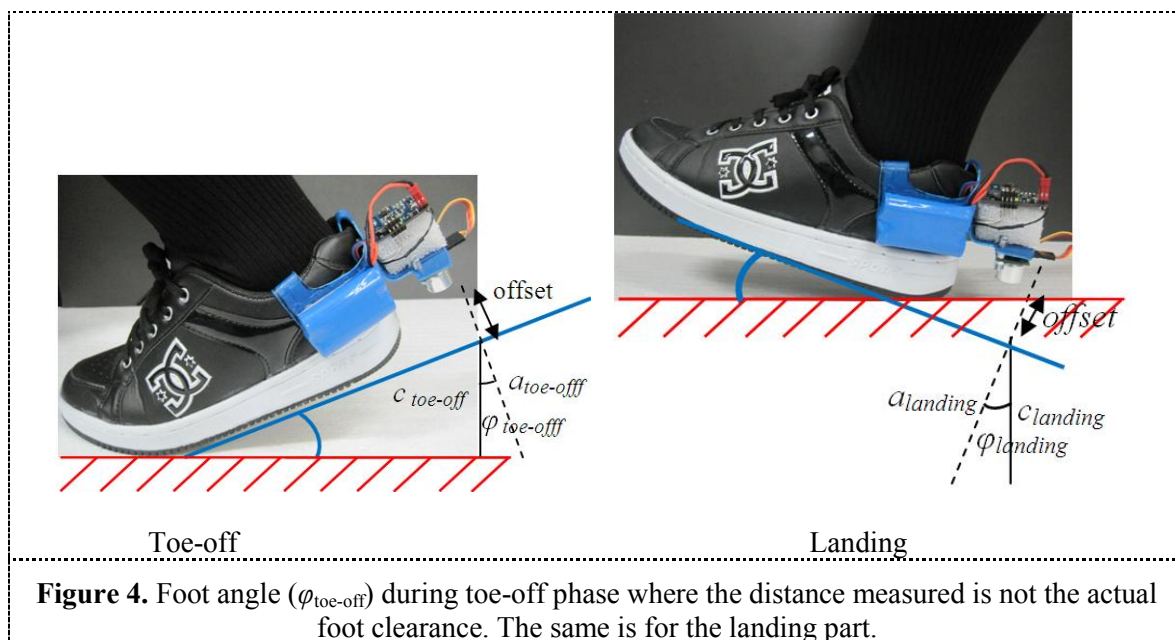
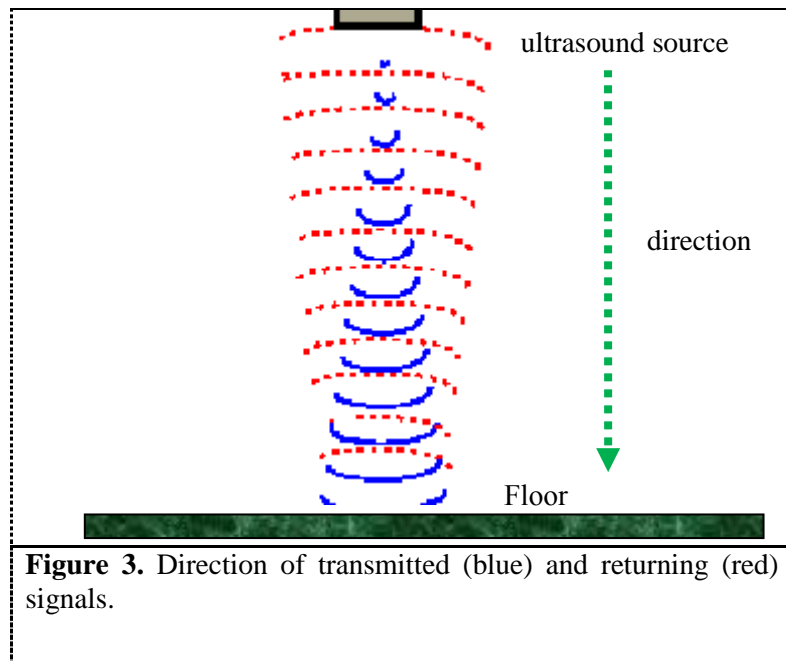
In order to measure the foot clearance measurement, the distance between foot and ground during walking is required. For this application, the ultrasonic system is used. The system consists of transceiver, controller board and wireless communication. The system is easily to attach to the shoes as wearable unit. This wearable unit is user friendly and low cost.

Figure 2 shows the block diagram of the measurement system. The ultrasonic signals with a frequency of 40 kHz are used with a target of maximum distance about 17cm. The maximum range was referred to the maximum of foot clearance as stated in [2]. The burst transceiver is recorded during sends by wireless communication processing consist of controller board and plotted as graph in custom design Gait Analysis Software. The foot clearance measurements directly plotted in the graph clearance versus time. Hence, the gait pattern captured. But, it is necessary to wait for the data to complete its transfer via wireless in order to get a stable data and optimum gait pattern. The power supply is the 7.4 V 1000 mAh Li-Po battery.



2.2. Problem Statement

Ultrasound based sensing requires straight line arrangement as the signal travels that way [9]. However, when measuring the foot clearance during gait events and phases such as toe-off, landing, stance, and swing, the ultrasonic sensor is not parallel to the ground. It is resulting non actual distance measured for foot clearance. The situation is described in Figure 3 and Figure 4.



2.3. Proposed Solution : Error Correction

To solve the problem occur, the inertial measurement unit sensor (IMU) is used to detect the angle between foot and ground as shown in Figure 5. All parameters including yaw, roll and pitch are shown and can be detected by the IMU.

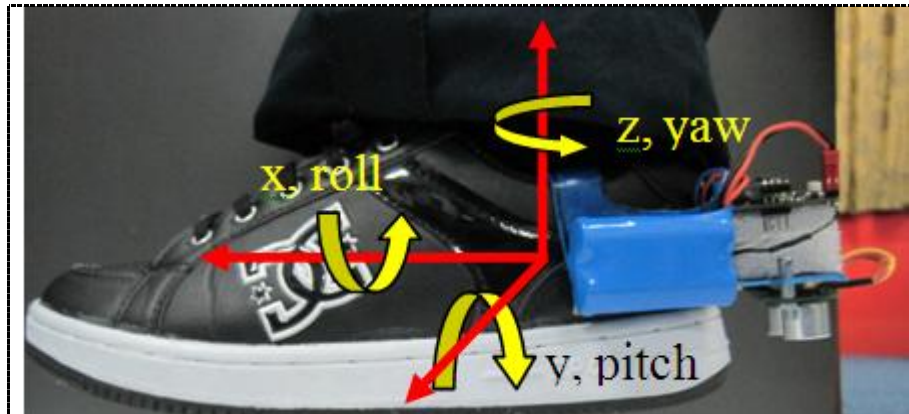


Figure 5. Yaw, Roll and Pitch

Then, the angle is used to correct the distance measured by ultrasonic sensor for foot clearance purpose. Besides that, the inertial measurement unit also gives the foot orientation data for roll and pitch data. Using trigonometry approach as shown in Figure 6, the angle identified is fed to the algorithm for real time foot clearance data correction. The equation (1) is valid to be applied during toe-off phase while equation (2) is valid for landing phase.

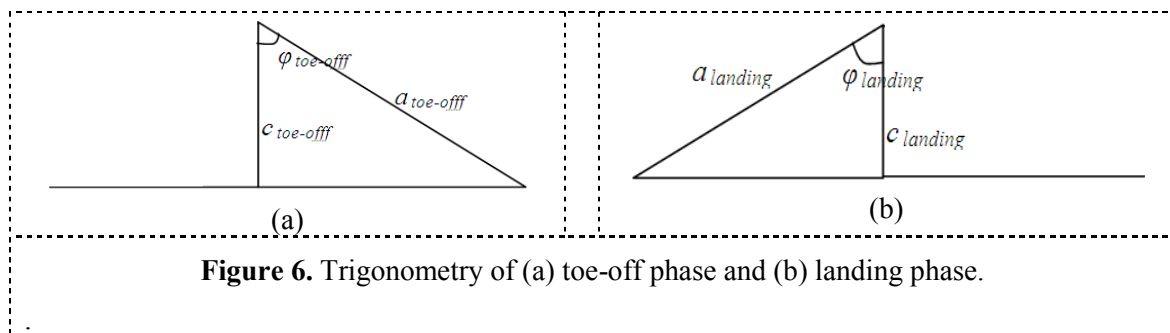


Figure 6. Trigonometry of (a) toe-off phase and (b) landing phase.

$$c_{toe-off} = a_{toe-off} \cos \varphi_{toe-off} \quad (1)$$

$$c_{landing} = a_{landing} \cos \varphi_{landing} \quad (2)$$

where c is the foot clearance in mm, φ is the angle between the foot and the ground and a is distance measured by ultrasonic sensor in mm.

This system is attached at the back of subject shoes using a special attachment unit. So the subjects wore their own shoes. While the controller board was attached on top of the attachment unit with

covered by heat shrink as shown in Figure 6. By applying the wireless transmitter to the board, this system can be operated wirelessly. Each subject is required to walk freely. The data captured and recorded immediately in graph form and numeric value. The data collected from the healthy subjects is used as a reference pattern for the un-normal gait analysis.

2.4. Data Processing

Output from the sensor was processed by controller board into digital representations and will be sent for data collection and captured through wireless communication as discussed before. The wireless communication can support up to 1.5 km in line-of-sight and up to 100 m for non line-of-sight. A second-order zero phase forward and reverse digital Butterworth low pass filter with a 20 Hz cut-off frequency was used to get the smoothed signal.

2.5. Experimental Setup

To verify that our newly developed system with the correction capability is functioning as intended and physically acceptable for our target application, a number of tests are performed. It started with the weight test using digital weight scale. After that, a complete system operation is performed which includes application of the attachment unit on a healthy subject and allow him to walk for 30 minutes freely in an outdoor setting. The third and last test is performed involving a ruler with a stand to allow straight vertical measurement representing clearance. A shoe attached with the measurement unit at the back is held with certain constant pitch angle. The readings are taken at certain clearance values. Further explanation is given in the next section with the results.

3. Results

Figure 7 shows the attachment unit with ultrasonic system. The whole attachment unit (without the shoes) is placed on a weigh scale, so that only the weight of the attachment unit with the battery is measured. The total weight of this attachment unit with ultrasonic system is 82g. The low weight of this system is not affecting the normal gait as state in [10] the attached system must not more than 300 g. Friction is not included in the experiments as it is not affecting foot clearance readings.

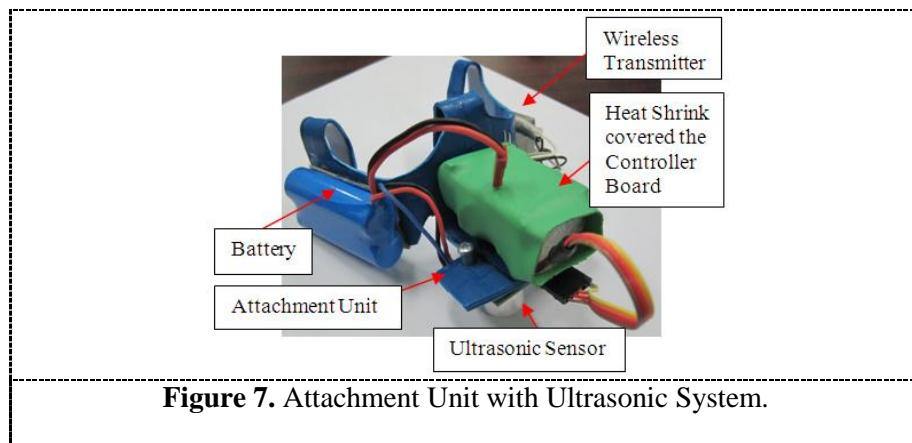
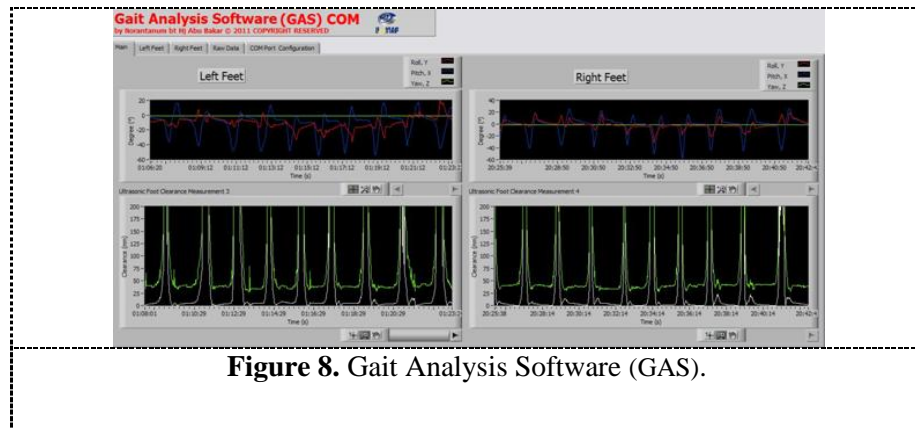


Figure 8 shows the Gait Analysis Software output screen. This Gait Analysis Software (GAS) has six tabs. There are main tab, right foot tab, left foot tab, raw data tab, com port configuration tab and data table tab. The clearance measurement and orientation graph are displayed in the GAS screen display.



In Figure 8 the corrected values and the ultrasound uncorrected values are shown. The correction can be seen more clearly in Figure 9. The correction is based on the algorithm using the trigonometry concept as represented by Equation (1) and Equation (2) as explained in the section 2.3. Figure 9 shows the technical view of clearance measurement for healthy subject during walking. Continuous clearance data collection for a period of about 30 minutes enables the system to be able to produce the gait pattern for the subject. The graph shows the gait pattern for right feet. The corrected data (clearance measurement) is represented by the white line. The numeric value for raw data from ultrasonic sensor and the clearance measurement are also displayed.

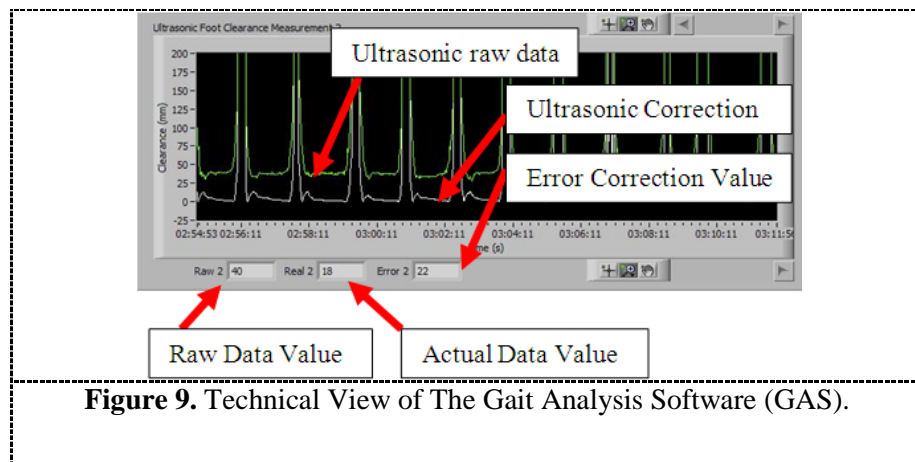


Figure 10 shows the experimental setup for proving of error correction. In this experiment, the ruler is used for the reference data. The ruler is vertically so that it is parallel to the wall. The ultrasonic system and the shoe is raised gradually along the ruler and clearance is measured every 1cm. The distance measurement of the attachment is transferred wirelessly to the GAS with the error correction.

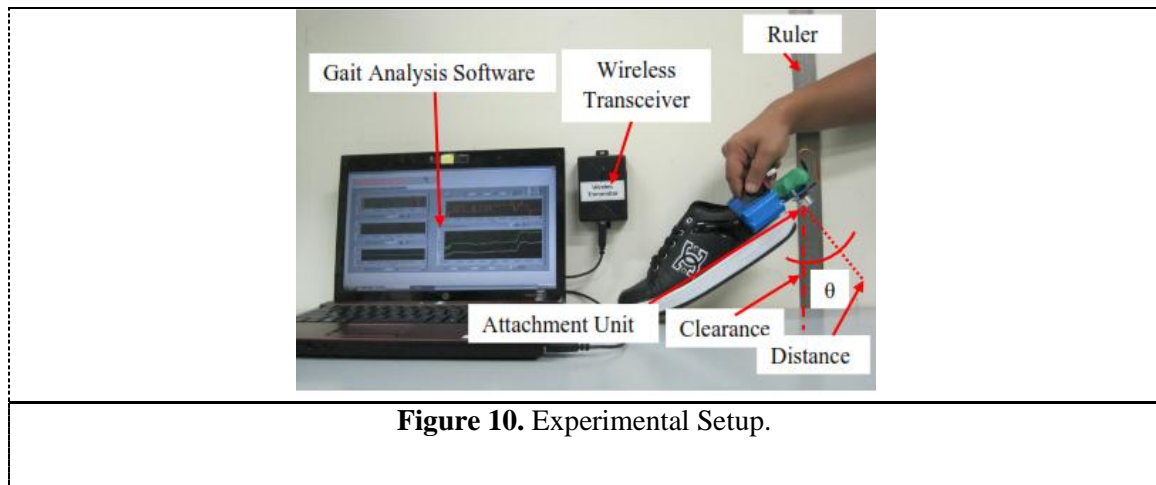


Table 1 shows the experimental data of several distance values obtained from our ultrasonic system measurement, with and without error correction. From the table, the comparison between reference data and the corrected ultrasonic system reading proves that our ultrasonic system gives acceptable results. Therefore, our ultrasonic system can be used for foot clearance measurement.

Table 1. The Corrected and Uncorrected Readings from the test.

Reference Data (cm)	Uncorrected Reading (cm)	Ultrasonic System Reading (cm)
4	5.1	4.1
5	5.7	4.9
6	6.6	5.9
7	7.7	7.1
8	8.6	8.1
9	9.6	9.1
10	10.4	10.0

4. Discussion

Unfortunately, the current practice in measuring foot clearance mostly requires laboratory settings with the use of reflective or active markers, one or more video cameras, thread-mill or suitable floor and computer software running on suitable computers [1]. This type of foot clearance measurement may not be representative of real life activities of daily living, ADL based measurement in natural settings [11], such as at home or outdoor. Problems such as marker slippage may also occur even during laboratory measurement [1].

A more advanced technique is by the use the accelerometer, however, the required calculation that involves double integration of acceleration data yields erratic results due to the effect of drift and

errors [11-12]. The sensing of MFC using accelerometer based measurement on surfaces that are uneven, bumpy or during stair descend or ascend is obviously problematic as it is not directly measuring clearance but rather calculate it using acceleration data.

As current state-of-the-art instruments are mostly requiring exclusive research, clinical or rehabilitation laboratories settings, plus the fact that they are limited in simulating the real world activities of an individual [1,11], an in-shoe approach is undoubtedly a better option of implementation.

With the weakness of the previous research, this research comes out more reliable for gait analysis. Where, our technology has more features enable to use in real time measurement. In addition, the features are self-corrected, simple set-up, user friendly, cost effective, in-situ measurement, convenient and affordable make our ultrasonic system is the best way for gait analysis based on the foot clearance and foot orientation measurement.

5. Future Work

Data collection for foot clearance measurement from huge sample group can be evaluated using statistical analysis using the custom designed newly proposed sensory board, ultrasonic system. Our intention is to design a fully integrated system on chip ultrasonic sensing system monolithically. We also plan to implement the smart Gait Analysis Software which is directly inform the user about the gait condition whether user in normal gait or abnormal gait using the classifier.

6. Conclusion

From the result and discussion, we can conclude that our technology is acceptable for gait analysis measurement especially for foot clearance measurement and foot orientation measurement. This is because of every requirement for gait measurement was considered and finally proven in this paper as fulfilled such as low system weight, real time measurement capability, a simple set-up, user friendly, cost effective, in-situ measurement, convenience and affordable as discussed, proves that our technology is acceptable. With real time capability, the system is able to measure, process, transmit to a remote computer, accessed or displayed on the computer screen at almost the same instant, which is especially very critical for example in rehabilitation or monitoring of the elderly.

Acknowledgments:

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