Abstract: This paper presents a new strategy for the ultrasonic time of flight (ToF) estimation. This work is carried out in the framework of an assistive mobility project. It has been thought for solving the ToF estimation problem of overlapped echoes. They are produced by complex surfaces like subject’s legs and shoes. The proposed algorithm is based on fitting the model of the echo to the real echo signal.

Keywords: ultrasonic, echo fitting, walker

I. INTRODUCTION

Mobility is one of the greatest and most important human faculties, since it affects not only to person’s locomotive capacity and the ability to realize personal tasks, but it is also related to physiologic, social and emotional issues.

Robotics can help people with reduced mobility capacity. The assistive mobility has been largely studied, and many assistive devices have been developed. They can be classified basically in two groups: alternative devices and empowering (or augmentative) devices [1].

In partial mobility situations, it is medically interesting that the subject not be condemned to wheelchair. With augmentative elements, the patient can delay this moment and avoid the problems related to the continuous use of wheelchair.

In the Smart Walkers research field, the main research lines are: Physical support, sensorial assistance, cognitive assistance and health monitoring. In this context, the novelty of the SIMBIOSIS purpose is that it pretends to be a multimodal biomechanical interface platform. Some biomechanical parameters are considered to identify postures, gestures, and actions to obtain a cognitive interaction between the user and the walker. These parameters will be used in the guidance of the robotic walker and to improve the user’s safety avoiding falls.

In the literature, human gait has been analysed taking into account the lower limb joint angles [2]. Usually, the study of human gait has been carried out by photogrammetric systems, inertial sensors, etc., that obtain good results in laboratory but it is not appropriate in a non intelligent ambient.

In previous works in the framework of the SIMBIOSIS project, assisted human gait have been analysed by employing the direct transmission ultrasonic technique [3]. This technique implies that the user must wear ultrasonic receivers. However, it is important to perform a study in a more realistic situation, in which the user does not need to wear any kind of sensors.

In the present paper, a non-wearable technique to estimate the relative position of the feet and their position with respect to the walker is proposed. This is performed with pulse-echo technique.

This paper is organized as following. First, in section II, we present SIMBIOSIS platform and the signals that will be studied. In section III, a brief study of the state of the art of ToF techniques are presented with their lack of accuracy in the case of overlapped echoes. The model echo and the model-echo fitting strategy will be shown in section IV. Finally, some experimental results and conclusions are presented in section V.

II. SIMBIOSIS PLATFORM

The SIMBIOSIS project is a multimodal biomechanical platform for predictive human-machine cooperation. SIMBIOSIS consist of three different and interconnected subsystems that configure a human-machine interface (HMI), figure 1.

1) The Upper-limb Force Interaction subsystem is compound by a set of force sensors installed on the walker’s handle.

2) The Lower-limb kinematics subsystem is compound by series of inertial sensors placed on each segment of both legs of the user.

3) The User-walker relative position subsystem use ultrasonic technology. This subsystem is studied in this paper.

The User-walker relative position subsystem is designed to determine the relative position between each foot and the walker and the position between the feet. To measure these variables, the pulse-echo technique is selected. Such technique has
be extensively studied in the literature [4], and it is based on the time elapsed between the acoustic transmission and the reception of the echo from the target. The arrived time of the echo can be detected through many different techniques that provide different accuracies.

Some of these techniques will be discussed in the next section, paying attention to their limitations for the type of signal obtained in the presented situation.

Figure 1. Subsystems schema and picture of the SIMBIOSIS.

The main problem is that the echoes produced by the reflection of the ultrasonic wave on the feet present many overlaps, due to complex geometries. The first reflector shape and its position are changing at the same time that the user’s feet are in movement. This is the most significant difference with the structured and known industrial environment.

The overlapping of echoes produces that the signal of the ultrasonic receiver has “humps”, and it is quite different from pure echo (Figure 2).

Figure 2. Signal and envelope from overlapped echoes.

In order to estimate the position of the feet in the ground and their evolution during the assistive gait cycle, high accuracy is necessary.

III. ToF TECHNIQUES REVIEW

In the literature there are many studies regarding accurate ToF echo-pulse techniques, which provide high accuracy when the target has a simple and fixed surface (cylinder, plane, corner…), and the echo signal has known and repetitive morphology (Figure 3).

Figure 3. Signal from non overlapped echo.

The most relevant and representative techniques are Threshold methods, Simple Curve-Fitting methods and Correlation methods. All of these obtain high accuracy, in some case, close to 1mm [4][5].

The Correlation method is unbiased. It consists of a filter that contains the replica of the echo waveform [4]. The drawback of this method is that it needs to store one template for each waveform, and in the present case there are infinity forms. To implement Correlation method would need templates for unknown signals.

Figure 4. Threshold method and Simple Curve-fitting method in overlapped echo.

The Simple Curve-Fitting method uses normally a nonlinear least-squares method to fit a parabolic curve to the enveloped signal on the rising edge. Figure 4 shows the drawback of this method. When the echo has humps, it is possible to fit the parabolic curve in each hump with the same accuracy, because the wave has many rising edges, and all of them may be good if they are studied independently. To implement Simple-Curve Fitting method it would be necessary a difficult pre-processing to obtain the real rising edge.
The Threshold method is simpler than the above discussed methods. The ToF is estimated with a voltage threshold of envelope signal. Due to presence of noise, the threshold should be enough to avoid false positive. Figure 4 shows an example of this technique, and its limitations. If the signal was non overlapped the estimate of the ToF would be lower than the estimate of the ToF of the overlapped signal. In the conclusions section, a comparative between the Threshold and the proposed technique will be presented.

IV. IMPROVEMENT OF THE MODEL-ECHO FITTING

In this work a new strategy based on digital signal processing of the echo is presented. It provides accurate range measurement when the reflectors have unknown and complex surfaces.

This new strategy is an improvement of the model-echo fitting method. This improvement is due to: 1) a more complete echo model is used to fit; 2) the selection of the points for fitting is optimized.

The echo model used is presented in equation (1), represented above in figure 3 and has been proposed in [6].

\[ s(t) = C \cdot t^n \cdot e^{-at} \cdot \sin(2\pi \cdot f \cdot t + \theta) \]  

MATLAB Curve Fitting Toolbox is used for fitting the curve, and three parameters are fitted: the amplitude \((C)\), the frequency of carrier \((f)\), and the time of start of the echo \((t)\). The rest of the parameters, \(n\) and \(a\), depend on the transducers, and have been obtained experimentally.

In the first implementations, the frequency of the carrier was not taken into account like a fitted parameter, because the transducers that are used are resonant at a fixed frequency (40 kHz). However, experimentally has been proved that, due to the overlap, the frequency of the compound signal changes with the time.

In order to obtain a good fit, it is important to have signals with enough amplitude. In the present case, the echoes are generated by the reflection of the ultrasonic wave on the user’s shoes or slippers, which usually have very absorbent surfaces. This kind of surfaces provides echoes with low amplitude and SNR (typically 10dB for the used system).

To obtain signals with higher SNR, the acoustic energy transmitted is studied. There are two ways to enlarge this acoustic energy: 1) to increase the number of the pulse of the excitation, nevertheless, the number of the pulses is limited by the dead zone, which is the minimum distance that can measure; 2) to increase supply voltage of the transmitter up to the limit allowed by the transducer manufacturer.

One of the innovations of the proposed strategy is that it does not require the entire echo signal for fitting, only selected zone by SNR threshold and first and second derivate of the envelope signal is used for fitting.

SNR is used for rejecting the points of the curve that don’t have enough amplitude, and can be confused with the noise. On the other hand, first and second derivate of the envelope are used for discriminating where the envelope signal is in the growth stage and there is not too much overlapped. Figure 5 represents the fit zone by discontinuous line.

The size of adjustment zone has been limited by the minimum time of the adjustment zone that is fixed by one cycle of carrier (in the present case 25μs), and by the maximum that is fixed by six cycles (that is the time of model envelope growth).

In expression (2) is shown the interval of adjustment zone duration, where \(t_1\) is the time of the first point of adjustment zone and \(t_2\) is the time for the last point.

\[ \frac{1}{f} < t_2 - t_1 < \frac{6}{f} \]  

Taking to account that each overlapped echo signal is different to any other and the overlap occurs at different times, each signal has its optimal adjust zone. To solve this particularity, we use a quality fitting index (QFI) to quantify the quality of the fitting.

The QFI is calculated as shown equation (3), being \(y_i\) the distance and \(\hat{y}_i\) the estimated distance.

\[ QFI = \sum_{i=1}^{n} w_i \cdot (y_i - \hat{y}_i)^2 \]  

Figure 5. Model-real composed echo fitting in zone of fit.
Where \( w_j \) is the weight for each adjustment point and it is defined in equation (4).

\[
\frac{e^{-\frac{1}{n}j}}{e^{-\frac{1}{n}}} \quad (4)
\]

To define this function two aspects have been considered: 1) the numbers of points for fitting (n); 2) that the central points are less corrupted than the firsts, by noise, and than the lasts, by overlap. Figure 6 represents the \( w_j \) function.

To determine optimal fitting, four model-echo fitting, with different fitting zones, are carried out for each signal. The fit with the minimum QFI is selected.

V. EXPERIMENTAL RESULTS AND CONCLUSIONS

About five hundred measurements of echoes of the slippers have been realized to validate the proposed technique. Figure 5, previously presented, shows an example of the optimal adjustment for a typical overlapped signal.

To compare the improvement of the echo-model fitting technique with Threshold method, a shoe has been placed in six different distances, and in each distance ten measurements were taken. Then bias, standard deviation and total error were calculated for each distance. The results obtained are shown in figure 5.

As it can be seen, it has been demonstrated that the improvement of the model-echo fitting provides good results, with bias less than 1 cm, standard deviation always around 0.2 cm, and total error is confined between 0.2 and 0.9 cm, which means that the strategy is robust. The implementation of Threshold method provides in some cases better bias results than the new technique, for example for 45 and 50 cm. However, the standard deviation for these distances is worse than the standard deviation of the model-echo fitting. Moreover, total error shows low robustness.

Figure 6. Weight for quality fitting index.

Figure 7. a) Bias, d) standard deviation and c) error for our technique (M-E Fit) and for threshold method.

ACKNOWLEDGMENTS

This work was carried out in the framework of SIMBIOSIS project that is support by the Spanish National Program of R&D – DPI.

REFERENCES