Modelling and Simulation of an Ultrasonic Tethering Smart Wheelchair System for Social Following

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***Abstract*—Distracted navigation causes 20% of all powered wheelchair accidents. In social situations, wheelchair users must divide their attention between navigating the chair and conversing with an accompanying person. These conversations could lead to increased mental stress and distractions from maneuvering the chair. This project aims to eliminate the need to manually control a powered wheelchair when moving and conversing with an accompanying person, by controlling the wheelchair's path to follow beside a person. This includes identifying and determining the person's pose to control wheelchair navigation. The proposed ultrasonic tethering system was developed and simulated on Matlab and Simulink using models for ultrasonic sensors, amplification and filtering circuits, and a processing unit. Unlike infra-red sensors and cameras that are highly dependent on environmental light conditions, ultrasonic sensors are inexpensive and independent of environmental conditions. Simulation results determined wheelchair direction based on the accompanying person's position, suggesting that ultrasonic tethering can be used for side-by-side following. The simulation results can be used to determine circuit component parameters for developing an ultrasonic tethering prototype.**

***Keywords*— powered wheelchairs, smart wheelchairs, ultrasonic triangulation, ultrasonic tethering, social-following.**

I. INTRODUCTION

Powered wheelchair accidents may affect user mobility and can result in restrictions in activity and social participation [1] [2]. Accidents such as tipping and falling, accidental contact, and dangerous operations could be caused by distracted navigation of powered wheelchairs [3]. In social situations, powered wheelchair users must divide their attention between navigating the chair and conversing with an accompanying person (AP), thus causing distracted driving. As a solution that minimizes wheelchair control, a smart-wheelchair system that incorporates contactless tethering techniques from human-following mobile robots was implemented on Matlab & Simulink. As explained by the authors in [4]–[6], human-following may be beneficial for powered wheelchair users in situations such as:

- Hands-free wheelchair control while moving behind a caregiver/guide
- Participating in social interactions (i.e., conversations)
- Users needing immediate access to powered wheelchair, when walking or exercising.

Previous human-following wheelchairs followed the person from behind [4]–[6]. However, for comfortable conversations between the user and the AP, the wheelchair should follow the person from the side [7]. Human-following or tethering can be achieved using commercially available infrared range sensors, ultrasonic range sensors, cameras, or Lidar. Ultrasonic sensors output a voltage proportional to distance by using high-frequency pulses [8] that are not attenuated by environmental factors, such as humidity, dust, and light conditions [9]. The output voltage is stable for shorter object distances, unlike photoelectric sensors [10]. Therefore, ultrasonic sensors were chosen for the proposed tethering system.

This research simulated the proposed ultrasonic tethering approach for social-following. The model was developed on *Simulink*® Version 9.2 (R2018b) using the *Simscape electrical toolbox* to determine if ultrasonic tethering is a viable option for side-by-side following. The proposed tethering system consisted of three processes: AP identification, AP position determination using triangulation, and wheelchair navigation and control using thresholding [4]–[6].

II. MODEL DESIGN AND DEVELOPMENT

The simulation model consisted of three main sub-systems: AP module, ultrasonic receiver module, and processing unit. Identifying and determining the AP position was simulated by using the AP sub-system and the ultrasonic tethering sensor sub-system. Wheelchair navigation was achieved by determining wheelchair motor direction signals in the processing unit. The ultrasonic sensor placement for triangulation is shown in Fig 1. Two ultrasonic range sensors were used to determine the position and one piezoelectric receiver and a transmitter (beacon) on the AP were used for identification (Fig 3).

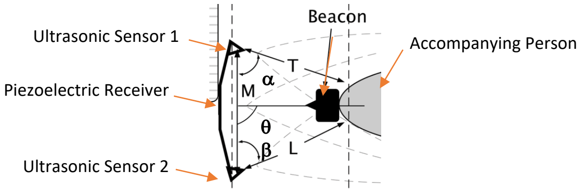

Fig. 1 Sensor placement on the wheelchair and beacon on the AP [9].

A. Accompanying Person Sub-system

The AP sub-system (Fig 2) consisted of a beacon that transmitted a 42 KHz ultrasonic signal for identification. This beacon would be worn on the AP side and consisted of an ultrasonic transmitter module and three message signals that modelled AP walking, turning, and stopping.

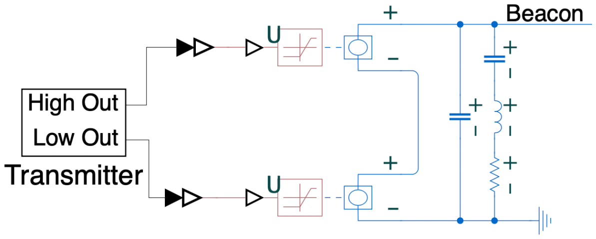

Fig. 2 Accompanying person sub-system for model identification, walking, turning, and stopping.

The ultrasonic signal was produced using a pulse generator and a *Simulink generic linear sensor* with a simplified Van Dyke equivalent RLC circuit model for a piezoelectric transducer. The circuit components and parameters for the Van Dyke model are real numbers; however, other models (Sherrit model, etc.) are complex numbers [11]. Real numbers are useful for simulations using real-world parameters. The message signals were used as the sensor's voltage, proportional to the AP distance. These signals were modulated with the 42 KHz signal to simulate the AP position.

The signals were modeled using the *Signal Builder* module in Simulink using,

$$a = m * \theta \tag{1}$$

$$a = n * d \tag{2}$$

where, a is the amplitude of the signal, m and n are constants of proportionality, θ is the AP orientation angle and d is the AP distance from the sensor. The 42 KHz pulse generator was designed to produce 0 – 5 V square wave pulses with a 50% duty cycle using a PWM generator. The transmitter circuit consisted of a voltage doubler that converted digital pulses from 0 – 5V to 0 – 20V and a voltage inverter that inverted and pulled down the 0 – 20V to ±10V to drive a piezoelectric transducer.

B. Ultrasonic sensor module

The ultrasonic range sensor module was designed to determine the AP pose by producing an analog voltage proportional to the AP distance. The analog voltage output is given by [8],

$$d = (v_{sound} * ToF)/2 \tag{3}$$

where d is the AP distance, v_{sound} is the speed of sound in air and ToF is the time for the pulse to travel from the sensor to the AP and the time for the reflection from the AP to the sensor (round trip time-of-flight). The system consisted of two identical range sensor modules to measure the distance from two distances for triangulation. The sensor module consisted of an ultrasonic pulse generator and amplification and filtering circuits. The ultrasonic range sensor consisted of two *Simulink generic linear sensors*, to convert the pulsed output from the transmitter and modeled as the piezoelectric transducers present in an ultrasonic range sensor (Fig 4). Each of the generic linear sensors had an input to output signal ratio of 1:100 to model output signal behavior and attenuation for real-world situations.

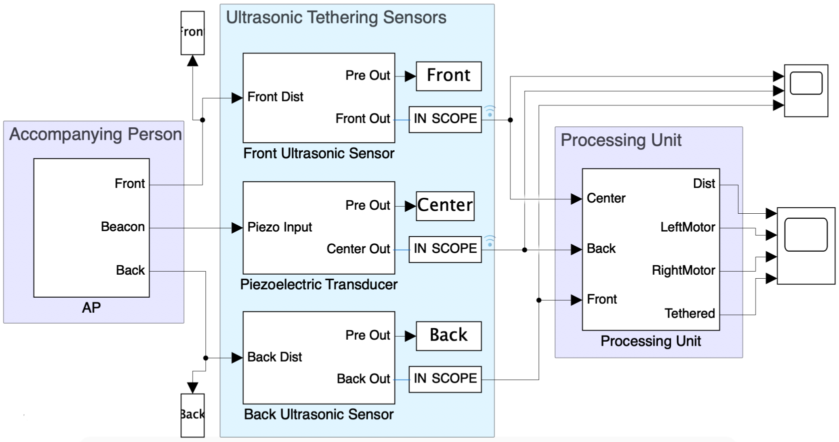

Fig. 3 Ultrasonic tethering model in Simulink.

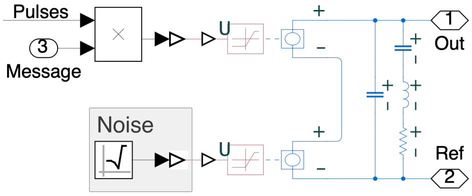

Fig. 4 The ultrasonic range sensor module for determining pose.

Noise was modulated to the message signal and was amplified and filtered using the amplification and filtering circuits simulated using the *Simscape toolbox* on Simulink [12]. The amplification circuits (Fig 6) amplified the signal change from a millivolt range to a microcontroller readable 0 – 5V range, using an amplifier. The filtering circuit (Fig 6) included an active low pass filter and diode-based amplitude demodulator to extract the message signal from the amplitude modulated ultrasonic signal. This determined the voltage proportional to the AP distance.

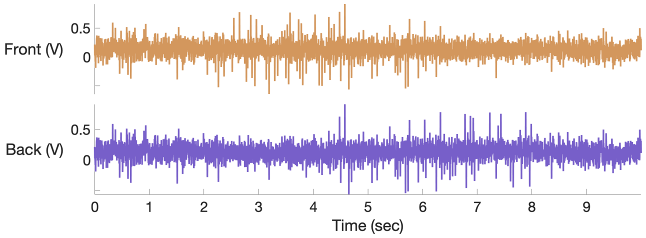

Fig. 5 Noisy signal generated by front and back ultrasonic range sensors.

The resistor and capacitor values (Rg, R1, C1 and C3) for each sensor circuit was determined and optimized using *Simulink Design Optimization* toolbox, specifically, the *Parameter Estimation* tool. The criteria used for estimating the circuit parameters were:

- High signal-to-noise ratio.
- Output signal limit between 0 and 5V to eliminate information loss due to ADC clipping.
- Passive components with values that are readily and commercially available.

C. Piezoelectric ultrasonic receiver module

The piezoelectric ultrasonic receiver identified the AP within the receiver's field of view by reading the beacon signal [9]. The receiver included an ultrasonic transducer and amplification and filtering circuits (Fig 6). A *noise function* was added to the beacon message signal and was amplified and filtered using an identical amplification and filtering circuits from section B.

D. Processing unit

The processing unit simulated a microcontroller and was used to process the sensor signals and produce motor drive control signals using a *Matlab function block*. This function determined left and right motor direction signals by calculating the tether distance from the front and back, and identified the AP from the center sensor signals using thresholds and comparing the front and back sensor signals. Comparing front and back signals indicated the forward and backward AP direction. The tether distance is given by [9],

$$distance = \sqrt{\frac{L^2 + T^2}{2M}} \qquad (4)$$

where, L^2 and T^2 are distances from two ultrasonic range sensors to the AP and M is the distance between the two sensors from Fig 1. Optimized thresholds were based on the expected AP motion (i.e., for every AP direction, the expected wheelchair direction was calculated from the tether distance, using eq. 4).

III. RESULTS

The system was simulated using an *ode15s* solver on Simulink and all outputs were stored as Matlab variables for displaying using the *To Workspace block*. An average of 7 iterations occurred for optimizing each parameter for different conditions; such as, AP walking, turning, and stopping.

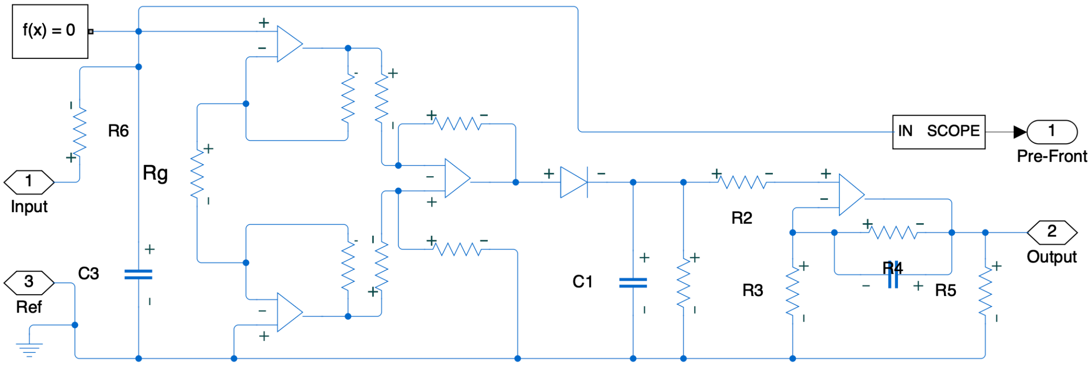

Fig. 6 Ultrasonic sensor amplification and filtering circuit

Table 1 shows the average optimized and final value parameters for each component for three circuits used in the simulation. The circuits had an average signal-to-noise ratio of 7.65 dB, a gain of 495 and cut-off frequency of 52Hz.

Table 1 Optimized component parameters using the Parameter Estimation tool and the final chosen values for each component.

Component	Optimized Value (units)	Final Value (units)
Rg	101.7 (Ohm)	100 (Ohm)
R1	9.2 (KOhm)	10 (KOhm)
R2	1.1 (KOhm)	1.3 (KOhm)
R6	1.4 (KOhm)	1.6 (KOhm)
C1	20.23 (nF)	22 (nF)
C2	0.1 (uF)	0.1 (uF)
C3	0.12 (uF)	0.1 (uF)

Optimized thresholds for the calculated tether distance are shown in Table 2. Sample results for the filtered front and back signals, and the AP distance from the sensors are shown in Fig 7 [9].

Table 2 Optimized thresholds for each AP direction.

AP direction	Avg. tether distance	Thresholds
Forward/Back	1.9 (V)	± 0.4 (V)
Right	1.4 (V)	± 0.4 (V)
Left	0.4 (V)	± 0.4 (V)
Stop	1 (V)	± 0.4 (V)

Sample wheelchair motor direction results for the left and right motors are shown in Fig 7. Wheelchair front and back direction was calculated by comparing the signals from the front and back sensors with each other. The wheelchair direction can be determined by using the left and right motor signals in a differential drive system.

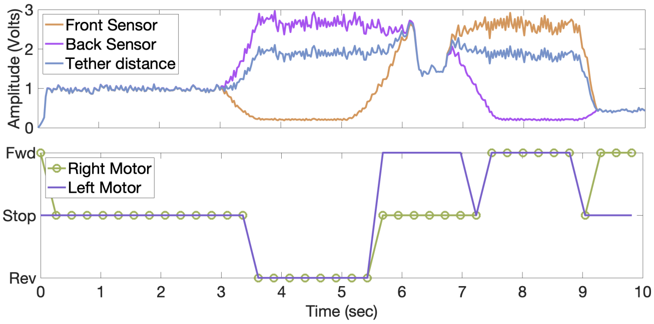

Fig. 7 Post-processed front (orange) and back (magenta) ultrasonic range sensor signals to calculate tether distance and calculated tether distance in volts (blue) and direction of left and right wheelchair motors.

IV. CONCLUSIONS

Ultrasonic tethering can be used for automatic powered wheelchair navigation beside a person accompanying. This paper simulated a smart wheelchair system with non-contact tethering to an accompanying person by determining the person's position with respect to the wheelchair. The proposed ultrasonic tethering system was modelled and simulated on Matlab® and Simulink®. The amplification and filtering circuit parameters were optimized to achieve required gains and cut-off frequencies for the circuits. The results showed that the accompanying person's position can be calculated using two ultrasonic sensors from which wheelchair motor signals can be produced. The simulation test criteria included testing different scenarios that included identifying and determining the person's forward, reverse, left and right motion with respect to the wheelchair. The system was designed to stop when the AP is outside the sensor field of view since the AP is considered untethered at that point. The simulated electrical circuits determined the optimum amplification and filtering circuits with active and passive components required to build an ultrasonic tethering prototype.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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