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KEY DESIGN PARAMETERS AND SENSOR-FUSION FOR LOW-POWER WEARABLE UWB-BASED MOTION TRACKING AND GAIT ANALYSIS SYSTEMS

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Abstract—Recently, we proposed a wireless ambulatory gait analysis system that provides a high ranging accuracy using ultra-wideband (UWB) transceivers. In this paper, we further investigate the performance of our proposed system including ranging using suboptimal templates, power consumption, and sensor-fusion. We show that the proposed system is capable of providing a 1.1 mm ranging accuracy (11.7 mm for current systems) at a signal-to-noise-ratio (SNR) of 20 dB using suboptimal-based receivers in industry accepted body-area-network UWB channels. For the angular-displacement, our system provides an accuracy that is less than 1° for the knee-flexion angle. This accuracy is superior to the accuracy reported in the literature for current technologies (less than 4°). Finally, we propose the integration of UWB sensors with force sensors. The system performance and design parameters are investigated using simulations and actual measurements. Ultimately, the proposed system is suitable for taking accurate measurements, and for tele-rehabilitation.

1. INTRODUCTION

Rehabilitation requires intensive and repetitive movement training that could last for months or even years to regain the lost functions. One major challenge that rehabilitation assessment faces is being able to monitor patients for long-times in domestic environments [1]. Among currently available accurate movement tracking technologies, optical tracking systems are the most accurate human locomotion

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tracking systems suitable for gait analysis. However, they require dedicated laboratories and specialized equipments. Basically, these systems are based on the estimation of the spatial coordinates of illuminated markers attached to the subject's body. It has been shown that measurement error on the three dimensional spatial coordinates or markers propagate unpredictably to the estimation of segment kinematics [2]. Hence, there is a need for low-cost, but accurate, systems that could provide support for long-term monitoring of patients at homes and outdoors.

Wearable ultra wideband (UWB) radios are capable of providing high ranging and positioning accuracies in challenging multi-path environments. This makes them a promising solution for accurate gait analysis and human locomotion tracking [3]. In particular, impulse-radio IR-UWB is a good candidate for such applications, where it has the potential for low-power and simple implementation [4].

In this paper, we study practical system design parameters and propose using sensor-fusion for a highly accurate human movement tracking system using UWB radios. In particular, we investigate the performance, power consumption, and sensor-fusion. Specifically, we estimate the power consumption-per-node. Furthermore, we propose the integration of force-sensors with UWB in order to estimate the body kinetics using our proposed full-body movement tracking system. Moreover, we provide results based on simulations and actual measurements. The organization of this paper is as follows. The proposed system, design parameters and power consumption are presented in Section 2. Then, senor-fusion is studied in Section 3 with simulation results provided in realistic channels. In Section 4, simulation results are provided using the IEEE 802.15.6a BAN channel model [5] as well as data based on actual measurements. Specific gait kinematic parameter results are provided for the estimation of the knee flexion angle using MATLAB simulations. Finally, conclusions are given in Section 5.

2. SYSTEM OVERVIEW, DESIGN PARAMETERS AND VERIFICATION

Our proposed human locomotion tracking system is based on wearable UWB transceivers (nodes) attached to the subject's body, or possibly sewn into clothing specifically designed for this application. Basically, UWB nodes measure the distances between the different points on the body during movement. Ranging data is acquired between the different nodes while the subject is walking through the estimation of the time-of-arrival (TOA) of the first path (which could be measured based on the fact that on-body nodes are synchronized), which is then converted to a distance estimates.

Ranging measurements include the intersegmental distances that have line-of-sight (LOS) links, as we proposed in [6, 7]. Our proposed system is designed based on a target ranging accuracy of $\approx 1\,\text{mm}$. The inter-marker distance measurement accuracy reported in the literature for current systems is equal to 11.7 mm [8]. Whereas, the reported error for angular displacement is up to 4.1° for knee-flexion angle [9], the upper-bound on the attainable angular displacement accuracy for our system is less than 1°. Now, we study the theoretical system performance and design parameters, and provides simulations for the system under investigation in realistic environments. Actual measurement data is also provided. The employed receiver architecture in our system is depicted in Fig. 1. Based on the pulse-energy-to-noise-ratio E_p/N_0 requirement, we determine the expected system parameters through link budget calculations. Moreover, the estimated power consumption per node is provided.

2.1. Design Parameters

In order to guarantee a specific E_p/N_0, a system link budget should be studied. Commonly, a link budget design includes the choice of pulse-width, transmitted power, data-rate, and antenna gains for a target E_p/N_0, which in turn is based on a required E_p/N_0. The transmit power is chosen according to the maximum allowed power spectral density (PSD) which is $-41.3\,\text{dBm/MHz}$ and the bandwidth of interest ($W = 2\,\text{GHz}$). Another important parameter that defines the loss that the signal experiences at distance d is termed path loss and defined as $PL(d) = PL_0 + 10n\log(\frac{d}{d_0})$, where PL_0 is the path-loss at the reference distance d_0, and n is the path-loss exponent [12]. The received power

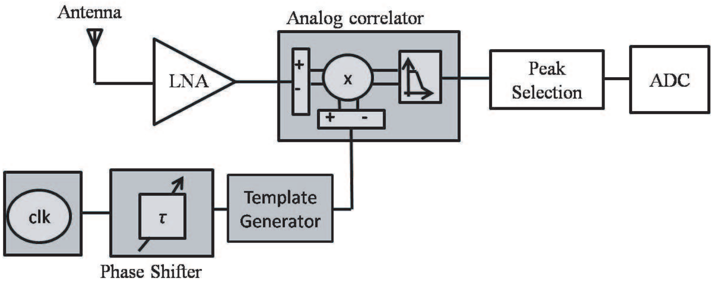

Figure 1. Receiver architecture based on the receivers in [7, 10, 11].

P_r at a distance d is [12]:

$$P_r(d) = P_t - PL(d) + G_r + G_t \tag{1}$$

where P_t is the transmitted power, and G_t and G_r are the transmit and receive antenna gains, respectively. For a target bit-rate $R_b = 1\,\text{kb/s}$, with a 2 GHz transmitted pulse bandwidth, −8.3 dBm transmitted power, 75.6 dB worst case total path-loss, −134.4 dBm average noise-power-per-pulse, 10 Kp/s pulse-rate, and 10 dB pulses-per-bit, the achievable bit-energy-to-noise ratio E_b/N_0 is 50.5 dB. This exceeds the required $E_b/N_0 = 18\,\text{dB} + 3\,\text{dB}$ (implementation loss) $= 21\,\text{dB}$ by 29.5 dB. Thus, the proposed system achieves the required E_b/N_0 with a 29.5 dB link margin. The minimum receiver sensitivity is −113.4 dBm.

2.2. UWB Ranging Measurement

For a further verification of the performance of the proposed system, actual on-body UWB measurements were taken at the MPRG[†] labs. Two UWB transmit and receive antennas were attached to the knee and ankle of the test subject in order to estimate the inter-spacing distance based on the TOA of the received pulses. The following equipments were used: HP33120A function generator, Tektronix CSA8000B Digital Sampling Oscilloscope, Geozondas pulser (GZ1106DL1, GZ1117DN25), and two antennas manufactured by the Virginia Tech Antenna Group. The test subject was allowed to walk forward and backward, and the received pulses were recorded and stored. Measurement data was further used in post-processing simulations in order to estimate the TOA and the corresponding distances. A sample received pulse along with the corresponding suboptimal sinusoidal template are shown in Fig. 2(a). The corresponding autocorrelation and cross-correlation functions are shown in Fig. 2(b). The resulting BER comparison between optimal and suboptimal template based detectors is shown in Fig. 3. According to the figure, suboptimal templates are traded for a negligible BER performance degradation. The detailed results will be provided and discussed in Section 4.

2.3. Power Consumption

This sub-section provides an estimation of the power consumption of the employed receiver based on state-of-the-art implemented UWB components proposed in the literature. The power consumption is estimated assuming 0.18 µm CMOS technology [13].

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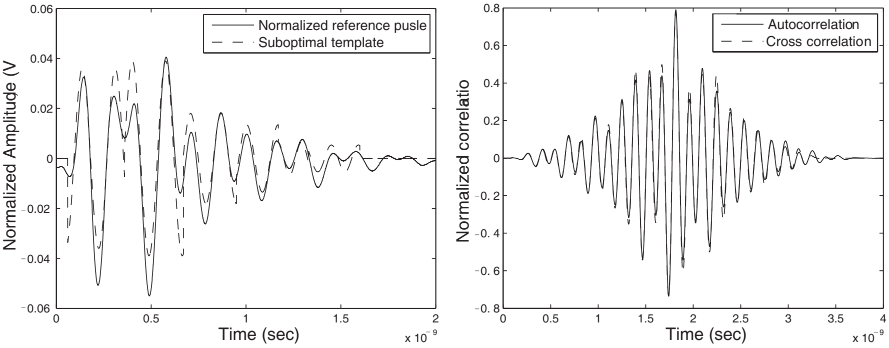


(a) (b)

Figure 2. (a) Sample received pulse from actual measurements along with the suboptimal sinusoidal template. (b) Corresponding autocorrelation and cross-correlation functions.

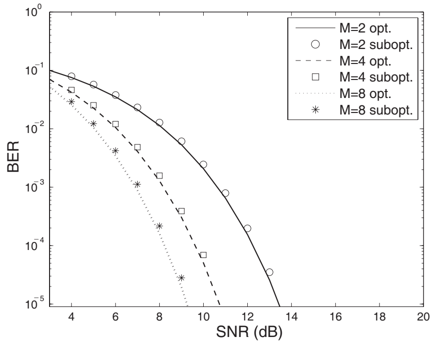


Figure 3. BER performance of M-ary EC-PPM modulation with optimal and suboptimal sinusoidal templates based on actual measurements.

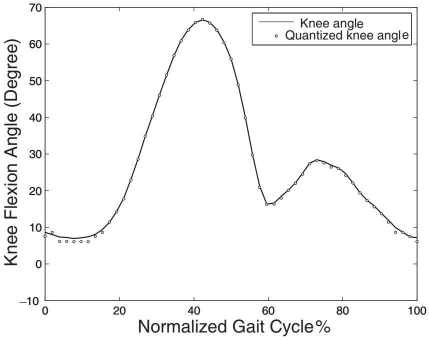


Figure 4. Knee-flexion angle for an adult with cerebral palsy (CP) assuming a 16-bit ADC compared to infinite-bits.

The analog-to-digital-conversion (ADC) represents a bottle neck for obtaining a low-power UWB receive [14, 15]. One possible solution to reduce the power consumption is to place the ADC after the correlator, and hence the correlation is performed in the analog domain. This relaxes the ADC requirements, and consequently reduces the overall power consumption [13]. In particular, moving the correlation operation from the digital domain to the analog domain reduces the required sampling frequency from the Nyquist rate to the pulse repetition rate [13]. However, the generation of the optimal template pulse in the analog domain is also difficult and power-consuming. An alternate solution is to use windowed-sinusoids, as they have the potential of accurately resembling the Gaussian pulse, and their generation in the analog domain is very straightforward [14,15].

Our chosen design parameters are as follows. For a 1 mm ranging accuracy based on the sliding-correlation receiver depicted in Fig. 1, according to our simulations, the required sampling time is $\Delta t = 10\,\text{ps}$. Thus, according to [11], for a phase-offset of receiver clock $\Delta\Phi_{Rx} = 360°$, $\Delta t = \frac{1}{360 * \Delta\Phi_{Rx} * f_{\text{PRF}}} = 10\,\text{ps}$ for a receiver clock frequency $f_{\text{PRF}} = 300\,\text{MHz}$. In [16] it was shown that the number of bits $n = 4$ bits is sufficient for reliable detection of UWB signals[‡]. However, due to the high required accuracy of the estimated gait parameters, our choice of the number of bits should be based on the accuracy of the reconstructed gait parameters. In Fig. 4 we present an reconstructed[§] knee-flexion angle using a 16-bit ADC compared to the original data for an adult with cerebral palsy. As can be seen, the 16-bit ADC provides the required accuracy. Thus, we assume a 16-bit ADC. For a signal bandwidth $W = 2\,\text{GHz}$, and $f_{\text{ADC}} = 500\,\text{KHz}$, and $n = 16$ bits, the power consumption of the ADC is 4.9 mW [18].

As provided in Table 1, the overall power consumption is less than 100 mW, when estimated for a 100% duty-cycle. According to [4], an average data-rate of 500 Kb/s is realized by the transmission of 1% duty-cycle of the 50 Mb/s maximum allowable data-rate, which can reduce the power consumption by a factor of 100 compared to the 100% duty-cycle transmission [4]. Equivalently, our system is realizable using a less than 1 mW power consumption per receiver unit. In addition to UWB sensors, we assume the use of force sensors placed underneath the subject's feet, in the form of sensor-fusion. The data acquired by these sensors is first converted to the digital format before it is transferred to the central-node[‖]. A 12-bit ADC provides a sufficient accuracy for the force sensors at a rate of 300 Hz. The corresponding power consumption is 2.5 µW.

[‡] The choice of n affects the ADC power consumption $P_{\text{ADC}} = \frac{2^n f_{\text{ADC}}}{\text{FOM}}$, where FOM is the figure-of-merit, and the quantization noise influences the BER [17].

[§] Spatio-temporal gait parameters are extracted from the sensor data, which is ranges in our system that are later on converted into three-dimensional coordinates. Typically, ranges are estimated in the analog domain, then converted into digital format via ADCs. Thus, the accuracy of conversion (quantization error) affects the reconstructed parameters.

[‖] We assume wireless connection between foot sensors and the central-node in order to minimize the number of wires used to allow for freedom of movement, and for a more comfortable wearable system.

Table 1. Power consumption summary.

	Power consumption	Ref.
LNA	12.6 mW	[13]
Correlator	31 mW	[11]
VCO + PLL	7.6 mW	[13]
ADC	4.9 mW	[18]
Digital cct.	14 mW	[17]
Buffers	27 mW	[11]
Total Power (100% duty-cycle)	97.1 mW	
Total Power (1% duty-cycle)	< 1 mW	

3. SENSOR FUSION

One of the advantages of UWB radios is their suitability for the integration with other motion sensors. With UWB sensors and inherent ranging and localization approaches, our system is capable of accurately estimating the gait kinematics. Ultimately, our system should be capable of estimating both kinematic and kinetic parameters associated with gait analysis. Thus, we further propose the use of force sensors placed under the test subject's feet. The analog data is first converted into the digital form, and transferred to the on-body central-node. This is typically analogous to the force plate used in optical tracking systems.

In order to examine sensor integrability and accuracy of the proposed system for actual gait parameters, gait data files acquired via force sensors were obtained from [19]. These files were processed using MATLAB to extract the gait data. The data was first converted to the binary format using a 12-bit ADC, as was described earlier, and then used in a simulation which was used as binary data in the IEEE 802.15.6a channel model. The detected bits were then reconverted and compared to original data in Fig. 5 for normal gait. The achieved BER was 7e-5 at $E_p/N_0 = 28\,\mathrm{dB}$, or equivalently $E_b/N_0 = 18\,\mathrm{dB}$ with 10 dB pulses-per-bit.

4. NUMERICAL AND SIMULATION RESULTS

This section discusses the approaches employed, and provides numerical results for the proposed system. In order to examine and compare the measurement accuracy of the proposed system to

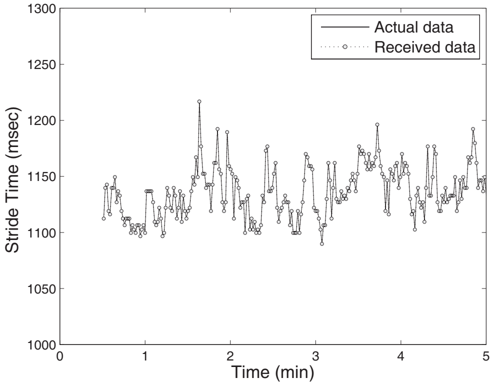
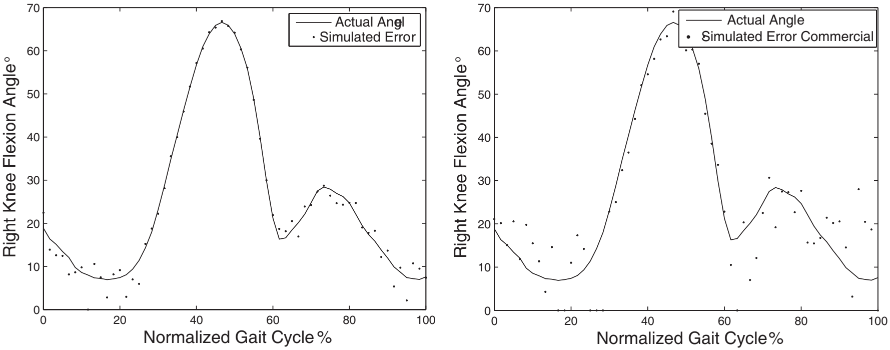


Figure 5. Comparison between stride time gait parameter for a healthy young subject extracted from force sensors [19] and simulated data in IEEE 802.15.6a using UWB radios.



(a) (b)

Figure 6. (a) Comparison of right-knee flexion angle from measurements [20] and proposed system simulation. (b) A comparison of right knee flexion angle from measurements [20] and commercial system simulation.

actual gait parameters, motion capture (MoCap) data files representing abnormal gait for a subject with cerebral palsy were obtained from [20]. These files were processed using MATLAB to extract the raw-marker data. The data was then used in a simulation which mimicked the inter-segmental distance measurement of the right-leg, and obtained the corresponding knee-flexion angle. The simulated results in the IEEE 802.15.6a channel model (along with the actual distances) are

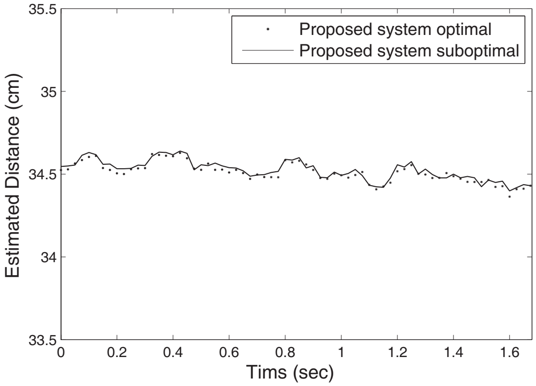


Figure 7. Comparison between the measured knee-to-ankle distance using UWB radios with optimal and suboptimal templates.

plotted in Fig. 6(a) for our system and Fig. 6(b) for a commercial optical tracking system for an adult with cerebral palsy (CP). The results show that the proposed system closely approximates the true angle. From the simulated linear-displacement (ranging), the attainable ranging accuracy for our system in the IEEE 802.15.6a is 1 mm at an SNR = 20 dB (assuming the suboptimal template). Moreover, the corresponding achievable angular-displacement is $< 1^\circ$.

In practical gait analysis systems, since the main target is to acquire the distances among the sensors during movement, the effect of the probable antenna displacement due to subject's movement ought to be considered. In our case, actual measurements were taken for the distance between the knee and ankle sensors at the MPRG labs, and the acquired pulses were further used in post-processing simulations assuming the receiver architecture depicted in Fig. 1. This was done in order to estimate the TOA of the received pulses, and obtain the corresponding Euclidean distance. The results are plotted for the optimal and suboptimal template based receivers in Fig. 7. From the results, the same performance of optimal TOA estimators is obtained using suboptimal templates at the expense of a 2 dB SNR requirement. Specifically, the optimal-template based detector required an SNR = 20 dB, whereas the suboptimal-based detector required an SNR = 22 dB to guarantee the 1 mm ranging accuracy. Nevertheless, this accuracy is achieved at low-power consumption.

The proposed system was also shown to be suitable for the integration of force sensors with UWB sensors with explicit results provided in Section 3.

5. CONCLUSION

This paper investigated a highly accurate wireless wearable full-body human locomotion tracking system for gait analysis based on body-fixed sensors using UWB technology. The proposed system provides a ranging accuracy of 1.1 mm for intersegmental linear distance measurements and less than 1° for angular-displacement, which are substantially better than the accuracies provided by current technologies. In addition, our system is capable of taking indoor and outdoor measurements, which makes it suitable for the assessment of mobility diseases and long-term monitoring required for tele-rehabilitation. The system design, implementation issues, power consumption, and error-performance of the system were discussed and extensive simulations were provided based on realistic environments. The proposed system also has the advantage of ultra-low power consumption, as the power consumption was estimated to be less than 1 mW per-node. Furthermore, the ranging capability was investigated and simulation results were carried out for the knee-flexion angle for subjects with CP. Moreover, results were presented based on actual measurements of the knee-to-ankle distance, which verified the achievable accuracy. Finally, the system was tested for the integration of force sensors with the UWB sensors, and was shown to achieve a good performance at an SNR = 18 dB. Hence, the proposed system has the potential for ultra-low power consumption, low-cost implementation, robust performance in realistic environments, as well as the integration with other types of sensors to provide a highly accurate full-body movement tracking system suitable for gait analysis.

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