



Cuffless Blood Pressure Estimation from Synchronized ECG and PPG Using Pulse Transit Time: An Embedded Acquisition and MATLAB Simulink Implementation

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ABSTRACT—

Cuff-based sphygmomanometry provides only intermittent readings and is poorly suited to continuous or wearable monitoring. This paper describes a low-cost cuffless blood pressure (BP) estimator that derives pulse transit time (PTT) from a single-lead electrocardiogram (ECG) and a fingertip photoplethysmogram (PPG). An AD8232 front end and a MAX30102 optical sensor are sampled at 200 Hz by an ESP32, which streams time-stamped samples over USB serial to MATLAB Simulink. The Simulink model filters both signals, detects the ECG R-peak and the PPG systolic peak, computes PTT beat by beat, and converts it to systolic and diastolic pressure with a linear calibration model whose slopes are negative. In a 30.43 s live recording the pipeline returned a PTT of 185 ms, pressures of 123.8/77.2 mmHg and a heart rate of 75.84 bpm. Against one simultaneous reference-cuff reading of 126/80 mmHg, the errors were -2.2 and -2.8 mmHg. This is a single-point plausibility check rather than a validation. Multi-subject calibration and accuracy assessment against the ANSI/AAMI SP10 criteria remain to be completed.

Index Terms—cuffless blood pressure, pulse transit time, photoplethysmography, electrocardiography, ESP32, MATLAB Simulink.

I. INTRODUCTION

Hypertension is one of the largest modifiable risk factors for cardiovascular disease. The World Health Organization estimates that 1.28 billion adults aged 30–79 years live with it, most of them in low- and middle-income countries, and fewer than half of them know their status [1]. Blood pressure (BP) changes continuously with posture, activity, stress and sleep, yet clinical practice relies on an intermittent oscillometric cuff. Each cuff measurement takes 20–30 s, becomes unreliable during movement, and cannot be shrunk into a wristband, patch or ring. These constraints motivate continuous, cuffless and wearable BP estimation.

Pulse transit time (PTT) is one of the most studied cuffless surrogates. It is the delay between a ventricular electrical event, marked by the ECG R-peak, and the arrival of the pressure pulse at a peripheral site, marked by the systolic peak of a fingertip PPG. A pulse travels faster through stiffer arteries, and arterial stiffness rises with pressure, so PTT tends to shorten as BP rises. The measurement is inexpensive to compute and rests on a clear physiological basis.

This paper makes three contributions. First, it describes a synchronized ECG–PPG acquisition chain built from low-cost parts and time-stamped on a single ESP32 clock. Second, it describes a MATLAB Simulink pipeline that performs filtering, beat-level peak detection, PTT computation and a linear conversion to systolic and diastolic BP. Third, it reports an end-to-end run on a live recording, together with a clear statement of what that run does and does not establish. Section II reviews related work, Section III presents the model, Section IV describes the system, Section V reports the results, and Section VI discusses limitations. Section VII concludes the paper.

II. RELATED WORK

Geddes et al. first showed that the transit time of the arterial pulse follows changes in blood pressure, which established PTT as a candidate noninvasive indicator [2]. Chen et al. paired the pulse arrival time with intermittent cuff calibration and tracked systolic pressure continuously during cardiovascular surgery, showing that a periodically recalibrated model can follow trends between calibration points [3]. Poon and Zhang formalized a cuff-less approach that uses simultaneous ECG and finger PPG and examined the PTT–BP relation over the working range [4].

Mukkamala et al. reviewed the theory and practice of PTT-based monitoring, compared the mechanistic models that relate wave velocity to stiffness and pressure, and identified calibration drift, the change of subject-specific coefficients with posture, vascular tone and time, as the central unsolved problem [5]. Kachuee et al. proposed a PTT-related algorithm that combines physiological and whole-waveform features and runs on mobile health hardware [6].

Two other families of methods are common. PPG-morphology and machine-learning approaches estimate BP from waveform shape. They need large labelled datasets and are sensitive to sensor placement, motion and skin tone. Arterial tonometry measures the pressure waveform directly at a superficial artery, but it needs careful alignment and is hard to miniaturize. The present work follows the PTT route because it uses inexpensive, compact sensors and a transparent model. Its cost is a per-subject calibration that must be repeated over time. The contribution here is integration and reproducibility, not a new BP model.

III. PHYSIOLOGICAL BASIS AND MODEL

A. Pulse Transit Time

For each heartbeat, PTT is the interval between the ECG R-peak and the PPG systolic peak:

$$PTT = t_{PPG} - t_R \quad (1)$$

The measured interval also contains a short pre-ejection delay between the R-peak and the onset of ventricular ejection. This delay is treated as roughly constant for one subject, so calibration absorbs it into the model intercept.

B. Relation Between Pressure and Wave Speed

The Moens–Korteweg relation gives the speed of a pressure wave in an elastic tube, with E the wall elastic modulus, h the wall thickness, r the internal radius and ρ the blood density [8], [9]:

$$PWV = (E \cdot h / (2 \cdot r \cdot \rho))^{1/2} \quad (2)$$

Bramwell and Hill expressed the pressure dependence in terms of the pressure–volume curve of the artery [7]:

$$PWV^2 = (V/\rho) \cdot (dP/dV) \quad (3)$$

Since the arterial wall stiffens as pressure rises, the wave speed increases and the transit time shortens. PTT and BP are therefore inversely related. Over the resting PTT range of roughly 150–350 ms, a smooth decreasing curve is well approximated by a straight line, so the estimator uses a linear calibration model.

C. Linear Calibration Model

The model maps PTT to systolic and diastolic pressure with separate coefficient pairs:

$$SBP = a_1 \cdot PTT + b_1, \quad DBP = a_2 \cdot PTT + b_2 \quad (4)$$

Here PTT is in ms, the slopes a_1 and a_2 are in mmHg/ms, and the intercepts b_1 and b_2 are in mmHg. The slopes must be negative, because a longer transit time corresponds to a lower pressure. The slope gives the change in pressure per millisecond of PTT, and the intercept gives the model value at zero PTT. Neither is a universal constant. Both depend on the subject's arterial stiffness, path length and sensor placement.

For a set of paired readings $x_k = PTT_k$ and $y_k =$ reference cuff pressure, the least-squares slope and intercept are

$$a = (N \cdot \sum x_k y_k - \sum x_k \cdot \sum y_k) / (N \cdot \sum x_k^2 - (\sum x_k)^2), \quad b = \bar{y} - a \cdot \bar{x} \quad (5)$$

A useful consequence of (4) is that pulse pressure, $SBP - DBP$, becomes $(a_1 - a_2) \cdot PTT + (b_1 - b_2)$. With the coefficients used here, pulse pressure grows as PTT shortens, which matches the usual observation that pulse pressure widens when arterial stiffness rises.

IV. SYSTEM DESIGN

A. Architecture

The system has four stages: synchronized ECG and PPG acquisition on an ESP32; streaming of time-stamped samples to a host PC over USB serial; signal processing and PTT computation in Simulink; and conversion of PTT to SBP and DBP with the calibrated model, shown on live displays. No cuff is used during measurement. Fig. 1 shows the stages.

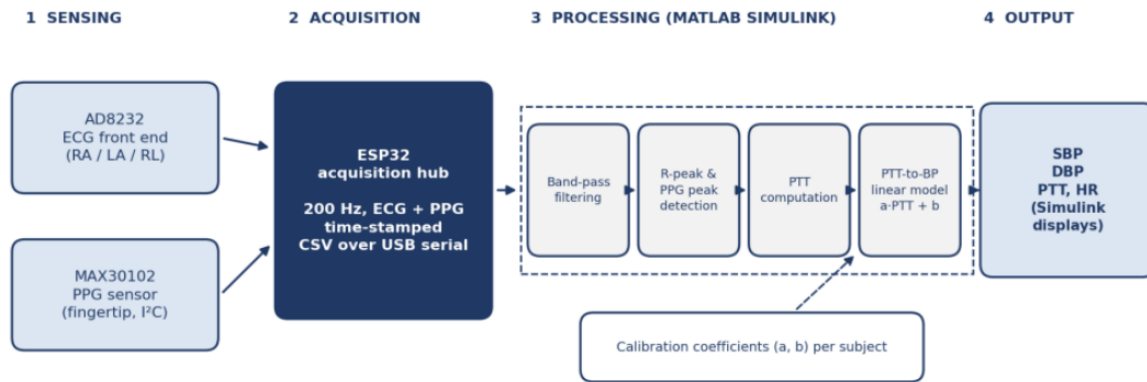


Fig. 1. Overall architecture: sensing, ESP32 acquisition, MATLAB Simulink processing and displayed outputs.

B. Hardware

The AD8232 is wired in a three-electrode (RA/LA/RL) configuration. Its analog output is read on GPIO34, and its leads-off outputs are read on GPIO32 and GPIO33. The MAX30102 is connected over I²C (SDA on GPIO21, SCL on GPIO22) and placed on the fingertip. It operates in red-plus-IR mode with an LED current of about 12 mA, a 411 μ s pulse width and a 16384 nA ADC range. Both sensors share the ESP32 3.3 V rail. Analog front-end noise is kept apart from the digital I²C and serial lines.

C. Firmware and Data Format

The firmware generates a 200 Hz tick from the microsecond timer. On each tick it reads the ECG as the average of four 12-bit conversions at 11 dB attenuation, takes the latest IR sample from the MAX30102 FIFO, and checks the leads-off pins. Each sample is sent as one comma-separated line at 230400 baud:

`n, t_ms, ecg, ppg, lo`

where *n* is the sample index, *t_ms* the millisecond time stamp, and *lo* the leads-off flag. Once per second the firmware also prints a diagnostic line beginning with “#”. That line reports the ECG and PPG ranges, the leads-off count and a rough heart-rate estimate, so signal quality can be checked in the serial monitor. The MATLAB scripts ignore these lines.

D. Simulink Processing

A preparation script loads the recorded CSV and creates the workspace variables *ecg_in*, *ppg_in*, *lo_in* and *Fs_ptt*. The Simulink model passes the three inputs to an Interpreted MATLAB Function block. A Demux then separates its seven outputs: SBP, DBP, PTT, heart rate, leads-off status, filtered ECG and filtered PPG. A band-pass and baseline-removal stage conditions both channels. R-peaks are found with threshold and derivative logic on the ECG. The matching systolic peak is located in the PPG within the following search window, and the PTT for each beat is passed to the calibrated model.

V. RESULTS

A. Recording

A live recording was saved as *live_demo.csv* and loaded into the workspace. It contains 6087 samples, which span 30.43 s at 200 Hz. This sampling rate matches the firmware, and the 30 s stop time of the simulation covers the record. The preparation script confirmed that the input variables were in the base workspace (Fig. 2 reproduces the Simulink model after the run).

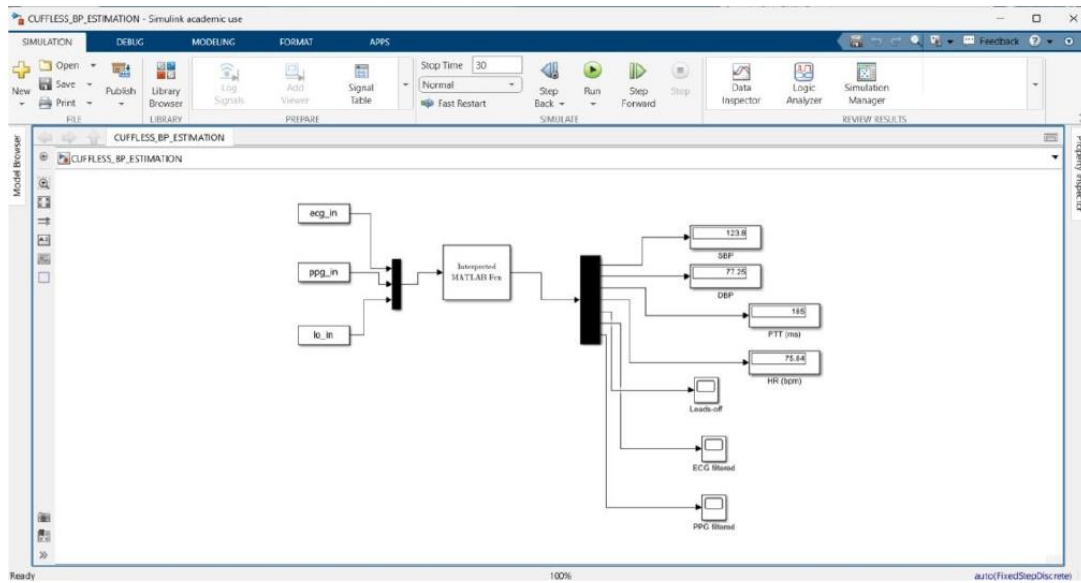


Fig. 2. Simulink model after running the recording: ECG, PPG and leads-off inputs enter the Interpreted MATLAB Function block, and its demultiplexed outputs drive the displays and scopes.

B. Model Output

The run returned the values in Table I. The heart rate of 75.84 bpm is typical of a resting adult.

TABLE I. SIMULINK OUTPUT FOR THE 30.43 s RECORDING

Quantity	Value	Unit
Recording length	30.43 (6087 samples)	s
Pulse transit time (PTT)	185	ms
Estimated SBP	123.8	mmHg
Estimated DBP	77.25	mmHg
Heart rate (HR)	75.84	bpm

C. Calibration Parameters

Table II lists the coefficients used in the model. With $PTT = 185.0$ ms the model gives $SBP = (-0.25 \times 185.0) + 170.0 = 123.8$ mmHg and $DBP = (-0.15 \times 185.0) + 105.0 = 77.25$ mmHg. The DBP value shown on the display is therefore 77.25 mmHg before rounding.

TABLE II. LINEAR PTT-BP COEFFICIENTS USED IN THE SIMULINK MODEL

Coefficient	SBP	DBP
Slope a (mmHg/ms)	-0.25	-0.15
Intercept b (mmHg)	170.0	105.0
Estimate at 185 ms (mmHg)	123.8	77.25
Pulse pressure at 185 ms (mmHg)	46.5	—

D. Comparison with a Reference Cuff

A reference cuff read 126/80 mmHg at the time of the recording. Table III compares the model with that single reading. The model was 2.2 mmHg low for SBP and 2.8 mmHg low for DBP, which lies within the 5 mmHg mean-error limit of the AAMI SP10 standard at this one point. The coefficients were not adjusted to match this reading. A single paired reading from one subject under one condition cannot test the spread of the errors or the slope of the model, so this result is a plausibility check and not a validation.

TABLE III. MODEL ESTIMATE VERSUS REFERENCE CUFF (ONE PAIRED READING)

Pressure	Model (mmHg)	Cuff (mmHg)	Error (mmHg)
Systolic (SBP)	123.8	126	-2.2
Diastolic (DBP)	77.2	80	-2.8

E. Interpretation

The chain works end to end on a live recording. It produces a plausible resting heart rate and pressures in a physiological range, with negative slopes and a pulse pressure that widens as PTT shortens. These results show that the pipeline functions. They do not yet show the accuracy needed for clinical use.

VI. DISCUSSION AND LIMITATIONS

The system sits between the intermittent cuff standard and the data-hungry PPG-morphology methods. It relies on one interpretable timing feature, so it needs little calibration data and it runs in real time on a host PC fed by an ESP32. The linear form keeps calibration to a straight-line fit and makes the model easy to inspect, because the sign and size of each slope can be checked against physiology.

The limitations are substantial. The result comes from one subject, one operating condition and one reference reading. A linear model is a local approximation of the underlying inverse relation, so it should not be extrapolated beyond the PTT range used for calibration. The coefficients also drift with posture, temperature and arterial tone [5], so periodic recalibration is needed. The peak detection has not yet been tested against motion artefact, a range of skin tones or varied finger placement, all of which affect PPG quality.

VII. CONCLUSION AND FUTURE WORK

This paper presented a cuffless BP estimation system that combines synchronized ECG and PPG acquisition on an ESP32, a MATLAB Simulink processing pipeline, and a linear PTT-to-BP model. A 30.43 s live recording gave a PTT of 185 ms, pressures of 123.8/77.2 mmHg and a heart rate of 75.84 bpm, which differed by -2.2/-2.8 mmHg from one reference reading. Future work will fit the coefficients to multi-point reference data, collect repeated trials across several subjects, evaluate mean error and standard deviation against the AAMI SP10 criteria, and test the system under motion. Further work will move the acquisition to a compact PCB with wireless streaming.

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