

Communication-Aware Adaptive Speed and Energy Control for a Low-Cost BLE Mobile Robot

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Abstract- Low-cost Bluetooth Low Energy (BLE) robots usually execute the last received command at a fixed duty cycle, so wheel-speed error, link degradation, obstacle proximity and energy use are not coordinated. This paper presents a lightweight communication-aware speed controller for an ESP32-class BLE robot and verifies it by Monte-Carlo simulation ($N = 100$ trials per condition). A Communication Quality Index (CQI), computed on board from packet loss, command latency and heartbeat freshness, is mapped to a speed limit. The target speed is the minimum of the communication, obstacle and motor limits and is tracked by an encoder-based PI loop. Five configurations (A0–A4) are compared in an ablation. In simulation, closed-loop control reduced tracking error at 75% speed from 52.2 to 0.81 RPM; CQI adaptation reduced unsupervised travel in a degraded-link mission by 89% (0.228 to 0.025 m) at the cost of 24% longer mission time and 7% more energy per metre; the obstacle term removed collisions that otherwise occurred in 16% and 50% of runs at 75% and 100% speed; and power-monitor fault latching cut stall energy by 87%. All results are simulation outputs under stated assumptions; hardware validation is outlined as future work.

Keywords- BLE mobile robot, communication-aware control, adaptive speed control, PI control, encoder feedback, energy efficiency, MATLAB simulation

I. INTRODUCTION

Wireless mobile robots are widely used for remote operation, inspection, education and industrial prototyping. A conventional low-cost robot receives motion commands over a wireless link and drives DC motors through an H-bridge. Fixed-duty, open-loop operation of such a robot does not account for wheel-speed mismatch, changing link quality, obstacle proximity or energy consumption, and when the link degrades the robot typically keeps executing its last command.

Communication-aware robotics, in which link quality and robot motion are treated jointly, is an established field [1]–[4], and reducing speed as network delay grows has direct precedent in Internet teleoperation [5]. The contribution of this

paper is therefore not the idea of coupling speed to the link. It is a specific, lightweight, locally computed design for a small single robot with a BLE link and no map, together with a quantified evaluation of what each element contributes and what it costs.

We address four questions. (Q1) Does CQI-based speed adaptation reduce unsupervised motion during link degradation, and at what cost in mission time and energy? (Q2) How much does closed-loop wheel-speed control improve tracking over fixed-duty control? (Q3) Which operating speed offers a good compromise between safety margin and energy per metre? (Q4) What heartbeat timeout balances stopping distance against false stops?

Because the hardware prototype is still being built, the questions are answered by Monte-Carlo simulation of a physics-based model of the robot, its BLE link and its operator, implemented in MATLAB. We state plainly that these are simulation results; Section VII lists the assumptions that hardware experiments must confirm.

II. RELATED WORK

Communication-aware robotics. Muralidharan and Mostofi review the field, covering channel prediction, path planning for connectivity and joint optimisation of motion and communication [1]. Zhang *et al.* give an overview of communication-aware motion planning and propose a joint communication–motion framework [3]. Caccamo *et al.* build online radio-signal maps with Gaussian random fields and use them to repair lost connectivity [4], and Gordon *et al.* convert ray-traced radio maps into risk maps for motion planning [2]. Most of these works decide where the robot should go, usually relying on maps or simulation, and often assume several robots or supporting infrastructure. A small single robot with no map and only a local BLE link is outside their scope.

Link-aware speed limiting. Slowing a robot when its control link degrades has precedent in teleoperation. Zhong *et al.* limit the speed of an Internet-controlled mobile robot according to a measured delay level so that path error stays within a tolerance [5]. The present work differs in the link metric (a composite of loss, latency and heartbeat freshness), in the platform (a BLE robot with a smartphone controller),

and in the evaluation (an ablation against open-loop, PI-only and obstacle-aware configurations, with energy per metre as an outcome).

Networked control and link estimation. Network delay and packet dropout degrade closed-loop performance and can cause instability [6]. In wireless sensor networks, link estimators combine information from several layers: Fonseca *et al.* show that merging physical-, link- and network-layer information improves estimates over single-source methods [7], and Baccour *et al.* survey the main estimator families [8]. The CQI follows the same principle of a composite local metric but is used to set a speed limit rather than to select routes.

BLE performance. BLE trades energy, latency and throughput through its connection parameters, and latency can rise sharply when bit error rates are high [9]. Tosi *et al.* review how BLE performance is measured [10]. Fürst *et al.* found that BLE behaviour on smartphones varies significantly with the phone chipset and operating system [11]; because the controller here is a smartphone, CQI thresholds should be calibrated per phone model. Spörk *et al.* show that BLE connections eventually deliver packets under interference but with sharply increased latency, and that an application can estimate this from connection-event timing [17]; the CQI uses the same observable (delay and loss at the receiver) for speed control.

Wheel-speed control, energy and obstacles. Bitriá and Palacín show that low-cost magnetic encoders introduce inaccuracies and control artefacts not captured in simulation, and discuss anti-windup and sampling time for a mobile-robot motor [12]. Energy-aware motion work uses DC-motor energy models to find velocity profiles [13] and energy-efficient motion plans [14]; here electrical energy is computed from the motor and supply model and reported per metre against speed and link condition. The dynamic window approach restricts a robot to velocities from which it can still stop before an obstacle [15]; the obstacle term below uses the same stopping-distance reasoning.

Positioning. To the best of the authors' knowledge, no prior study combines a composite BLE link-quality index, an obstacle-aware speed limit, encoder-based PI control and energy per metre on a low-cost robot in an ablation study. The contributions are: (i) a lightweight CQI with a hysteretic speed-limit map and heartbeat failsafe; (ii) an integrated speed-arbitration architecture, $\min(V_{comm}, V_{obs}, V_{motor})$, feeding a PI loop; and (iii) a reproducible simulation framework (MATLAB) with an ablation that exposes trade-offs, including the time and energy cost of adaptation.

III. SYSTEM AND CONTROLLER DESIGN

A. Platform and Baseline

The baseline robot (A0) is an Arduino Uno-class controller with an HC-05 Bluetooth module, an L298N driver and a four-wheel chassis; a smartphone sends single-character commands and the robot applies a fixed duty cycle without feedback. The proposed platform (Fig. 1) uses an ESP32-C3-class controller with BLE, encoder-equipped DC gear motors, a TB6612FNG-class driver, an ultrasonic range sensor and an INA219-class power monitor. The phone transmits the commanded speed and a sequence number every 50 ms; the sequence number also serves as the heartbeat.

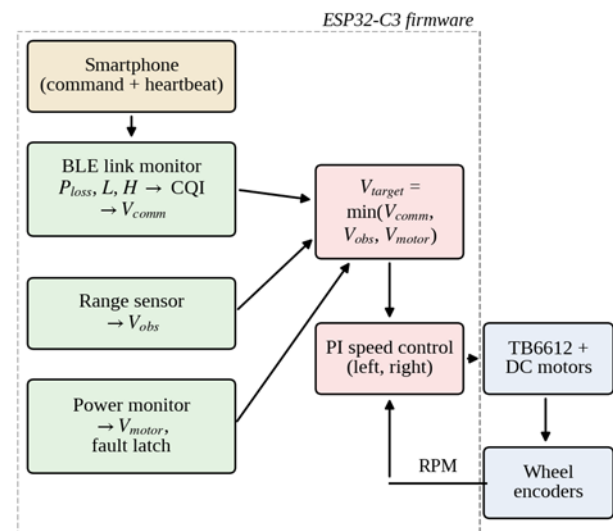


Fig. 1. Proposed control architecture. Three limits are arbitrated by a minimum operator before the wheel-speed PI loop.

B. Communication Quality Index

The robot estimates link quality from sequence numbers and arrival times. Over a sliding window of $W = 20$ packets that ends 0.3 s in the past (so that every packet has either arrived or passed its 0.3 s deadline), it computes the loss ratio P_{loss} and the mean latency of delivered packets, normalised by $L_{max} = 0.2$ s to give L_{norm} . A heartbeat term $H = \max(0, 1 - a/T_{hb})$ uses the age a of the newest packet and $T_{hb} = 1$ s; it reacts immediately to bursts that the delayed window cannot yet see. The raw index is

$$CQI_{raw} = w_1(1 - P_{loss}) + w_2(1 - L_{norm}) + w_3H \quad (1)$$

with $(w_1, w_2, w_3) = (0.4, 0.3, 0.3)$, clipped to $[0, 1]$. The index is smoothed by an asymmetric exponential filter (gain 0.6 when falling, 0.1 when rising), so degradation is acted on quickly and recovery is cautious. Combining several link indicators in one local metric follows the practice in link

estimation [7], [8]. The BLE specification gives applications no standardised link-quality indicator, and delivery latency grows under interference [17], which motivates computing the index in the application. With a healthy link the index settles near 0.96, not 1, because of the 20 ms mean BLE latency.

TABLE I
CQI-TO-SPEED MAP

CQI region	Speed limit	Level
≥ 0.85	100% of maximum	4
0.70 – 0.85	75%	3
0.55 – 0.70	50%	2
0.40 – 0.55	25%	1
< 0.40	stop (critical)	0

Moving up one or more levels requires the CQI to exceed the threshold by a hysteresis margin of 0.05; moving down is immediate.

C. Speed Arbitration and Failsafe

The commanded speed c (fraction of the maximum speed, 300 RPM) is limited by three terms:

$$V_{\text{target}} = \min(c V_{\text{max}}, V_{\text{comm}}, V_{\text{obs}}, V_{\text{motor}}) \quad (2)$$

where V_{comm} is the Table I limit. If the heartbeat age exceeds the timeout T_{to} (default 0.5 s) or the CQI level is 0, the controller enters a failsafe state and the target becomes zero; it resumes when the age is below T_{to} and the level is at least 1. V_{obs} follows the stopping-distance rule

$$V_{\text{obs}} = a(\sqrt{(T_1^2 + 2(d - d_s)/a)} - T_1) \quad (3)$$

with measured range d , safety distance $d_s = 0.15$ m, design deceleration $a = 3$ m/s² and latency allowance $T_1 = 0.15$ s [15]. V_{motor} is zero when the INA219 supply current exceeds 1.6 A for 0.3 s (stall or over-current), and the fault is latched until reset.

D. Closed-Loop PI Speed Control

Each wheel speed is estimated from encoder counts over the 50 ms control period (360 counts per wheel revolution, so one count equals 3.3 RPM). The duty command is

$$u(k) = K_p e(k) + K_i T_s \sum e(j), \quad e = \text{RPM}_{\text{target}} - \text{RPM}_{\text{meas}} \quad (4)$$

with output clipped to $[0, 1]$ and conditional-integration anti-windup. A first-order model identified from step tests of the nominal motor (gain ≈ 331 RPM per unit duty, time constant ≈ 0.09 s) was used for IMC-based λ -tuning [16] with $\lambda = 0.15$ s, giving $K_p = 0.002$ and $K_i = 0.02$. The gains were then checked by the step tests of Section V-A rather than tuned further.

IV. SIMULATION METHODOLOGY

A. Plant, Encoder and Power Model

Each wheel is a brushed DC motor with a gearbox, modelled by $J d\omega/dt = k_e i - b\omega - T_c \text{sgn}(\omega) - T_L$, with $i = (D$

$V_{\text{bus}} - k_e \omega)/R$ and duty D . The battery has internal resistance, so V_{bus} sags with load. Supply current is $D \max(i, 0)$, and electrical power is V_{bus} times supply current plus a constant 0.30 W for the electronics, so energy per metre includes idle consumption. Per trial, the motor constants vary by 4% (1σ), Coulomb friction by 15%, the battery voltage is uniform on $[5.5, 6.0]$ V, and a load torque step of 0.01–0.03 N·m is applied in E1. Encoder counts are the floor of the accumulated rotation, so quantisation is represented. Table II lists the parameters; they are representative of a small gear-motor robot and are not measurements of the prototype.

TABLE II
MAIN SIMULATION PARAMETERS

Parameter	Value
Wheel diameter / track	65 mm / 150 mm
Max. wheel speed	300 RPM (1.02 m/s)
Motor R , $k_e=k_t$	4.5 Ω , 0.173 V·s/rad
Inertia J , friction b , T_c	6×10^{-4} kg·m ² , 2×10^{-4} , 0.012 N·m
Battery / internal resistance	5.5–6.0 V / 0.5 Ω
Electronics power	0.30 W
Encoder / control period	360 counts/rev / 50 ms
PI gains K_p , K_i	0.002, 0.02
BLE: RSSI at 1 m, 50% PER point	−59 dBm, −88 dBm
BLE connection interval / deadline	30 ms / 300 ms
Path-loss exponent / shadowing σ	LOS 2.2 / 3 dB; NLOS 3.0 / 5 dB (+6 dB)
Trials per condition	100 (E7: 30)

B. BLE Link Model

Mean RSSI follows a log-distance law with exponent n , plus AR(1) shadowing (2 s correlation time), 2 dB per-attempt fast fading and optional burst interference (a two-state process that subtracts 20–25 dB). Each 50 ms command packet is attempted at successive 30 ms connection events, starting at a random offset, until it is delivered or the 300 ms deadline passes, mimicking link-layer retransmission. Each attempt succeeds with probability $1 - 1/(1 + \exp((\text{RSSI} + 88)/1.8))$. Packet loss therefore means “not delivered within 300 ms”, and latency grows with the retry count. The same link model is applied to all configurations, including A0, to isolate the effect of the controller rather than that of Bluetooth Classic versus BLE.

C. Configurations and Operator Model

The ablation uses five configurations: **A0** open-loop fixed duty, no failsafe; **A1** adds encoder PI control; **A2** adds CQI

speed limiting and the heartbeat failsafe; **A3** adds the obstacle limit; **A4** adds power monitoring with fault latching. **A0** and **A1** hold the last received command indefinitely. The operator sends the commanded speed with the sequence number every 50 ms. In obstacle trials the operator, who is assumed to be inattentive, issues a stop after a reaction delay uniform on 0.3–1.0 s once the wall is within 0.8 m. This is an assumed model and is the main driver of the collision rates of **A0**–**A2** reported below.

D. Experiments and Statistics

E1: tracking at 25/50/75% speed with a load step. **E2**: speed steps 0→50% and 50→80%. **E3**: stationary link characterisation, 1–15 m, 60 s per trial, LOS and obstructed. **E4**: a 14 m mission at 75% speed through a 4 m obstructed zone (12 dB extra loss, with burst interference), plus a sensitivity sweep of the zone attenuation. **E5**: abrupt link outage while driving, for heartbeat timeouts 0.2–1.5 s, and a 120 s false-stop test under burst interference. **E6**: approach to a wall at four speeds. **E7**: energy per metre over 10 m versus speed. **E9**: 3 s wheel stall. Unsupervised travel is the distance driven while the newest command is older than 0.5 s. Results are mean $\pm$ 95% *t*-interval; proportions use Wilson intervals; two-sample tests are Welch's *t* and Mann–Whitney *U*, and Fisher's exact test for collision counts. Seeds are fixed. The framework is provided as MATLAB code; the numerical results reported here were generated by an equivalent Python implementation with identical equations, parameters and experiment definitions.

V. RESULTS

A. Speed Tracking and Step Response (**E1**, **E2**)

Closed-loop control reduced tracking error by more than an order of magnitude (Fig. 2, Table III). At 75% speed the MAE fell from 52.2 to 0.81 RPM (Welch $p < 10^{-80}$). The open-loop robot settles roughly 23–51% below the target (depending on speed) and cannot reach 90% of either step, whereas **A1** shows a 10–90% rise time of 0.33 s, 2% settling time of 0.70 s and overshoot below 0.5%. Open-loop wheel mismatch also produces a large uncorrected lateral drift (42% of path length at 75% speed versus 3.8% for **A1**). The simulated encoder is ideal apart from quantisation, so hardware errors will be larger.

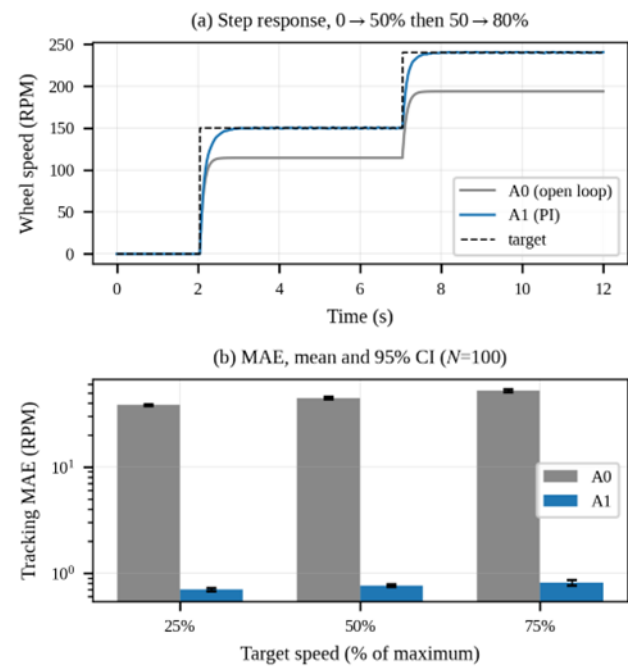


Fig. 2. (a) Step response of one trial. (b) Speed-tracking MAE after a load step (mean and 95% CI over 100 trials).

TABLE III

TRACKING AND STEP RESPONSE (**A2**–**A4** EQUAL **A1** WITH AN IDEAL LINK)

Metric	A0	A1
MAE at 25% (RPM)	38.3	0.70
MAE at 50% (RPM)	44.7	0.76
MAE at 75% (RPM)	52.2	0.81
Rise time 0→50% (s)	not reached	0.33
2% settling 0→50% (s)	not settled	0.70
Overshoot 0→50% (%)	0	0.46
Rise time 50→80% (s)	not reached	0.27
2% settling 50→80% (s)	not settled	0.44

B. Link Characterisation (**E3**)

In line of sight the link is essentially lossless to 10 m (loss 0.04%) and reaches 0.9% at 15 m. The obstructed channel degrades much earlier: loss is 2.8% at 4 m, 37.7% at 8 m and 87.3% at 15 m, with 95th-percentile latency rising from 34 ms to 276 ms (Fig. 3, Table IV). The CQI tracks this progression, falling from 0.96 to 0.17, so it is a usable monotonic indicator of link condition in this model.

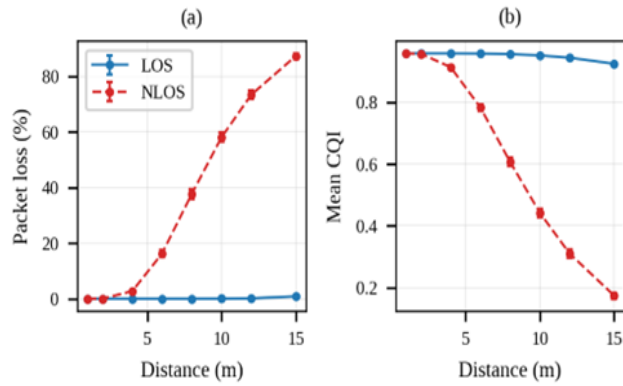


Fig. 3. (a) Packet loss and (b) mean CQI versus distance (mean and 95% CI, 100 trials).

TABLE IV
LINK STATISTICS VERSUS DISTANCE

d (m)	LOS %	loss ms	p95 NLOS %	loss ms
2	0.00	33	0.0	34
4	0.00	33	2.8	103
6	0.00	34	16.3	204
8	0.00	35	37.7	247
10	0.04	46	58.0	264
15	0.88	102	87.3	276

C. Degraded-Link Mission (E4)

Fig. 4 shows a trial in which the fixed-speed robot loses the link for about 1.5 s inside the zone and keeps driving, while the CQI-adaptive robot slows, stops on the heartbeat timeout and resumes after recovery. Over 100 trials (Table V), A2 reduced unsupervised travel from 0.228 ± 0.079 m to 0.025 ± 0.007 m, a 89% reduction (Welch $p = 1.5 \times 10^{-6}$; Mann-Whitney $p = 0.009$). The absolute distances are small at a 12 dB zone because bursts that actually exceed 0.5 s are infrequent; the effect grows with severity (Fig. 5): at 18 dB, unsupervised travel is 1.55 m for A1 and 0.08 m for A2.

Safety is not free. Mission time rose from 18.5 s to 22.8 s (+24%) and energy per metre from 1.58 to 1.69 J/m (+7%), because time spent slowed or stopped still draws the idle power. At 18 dB the adaptive robot completed the 14 m mission within 90 s in only 38% of trials (time to goal 63 s when it did). A3 and A4 are identical to A2 here because the mission has no obstacle or fault. Open-loop A0 finishes later than A1 (21.9 s) simply because it drives slower than commanded.

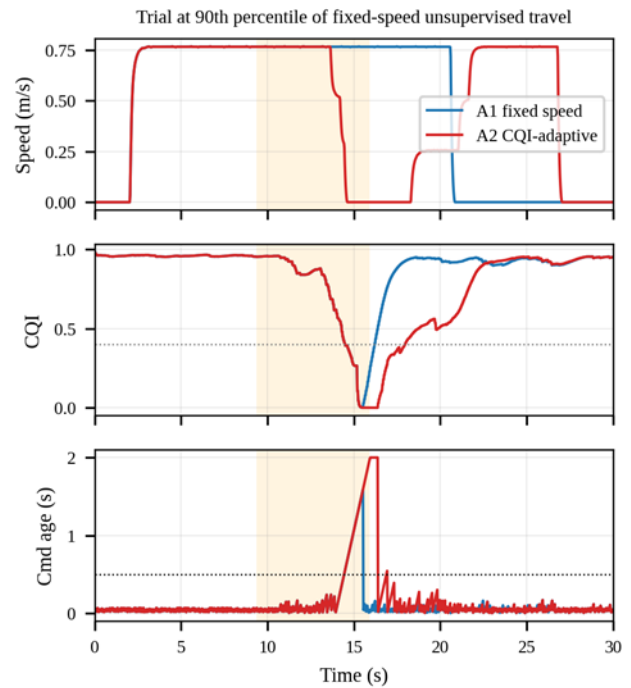


Fig. 4. Mission trial at the 90th percentile of fixed-speed unsupervised travel: speed, CQI and command age. Shaded: obstructed zone.

TABLE V
DEGRADED-LINK MISSION, 12 DB ZONE (MEAN $\pm$ 95% CI)

Config.	Unsup. travel (m)	Time (s)	Energy (J/m)
A0	0.255 ± 0.069	21.9 ± 0.1	1.60 ± 0.02
A1	0.228 ± 0.079	18.5 ± 0.0	1.58 ± 0.02
A2–A4	0.025 ± 0.007	22.8 ± 0.9	1.69 ± 0.03

All configurations completed the mission in every trial (zone 12 dB, 90 s limit).

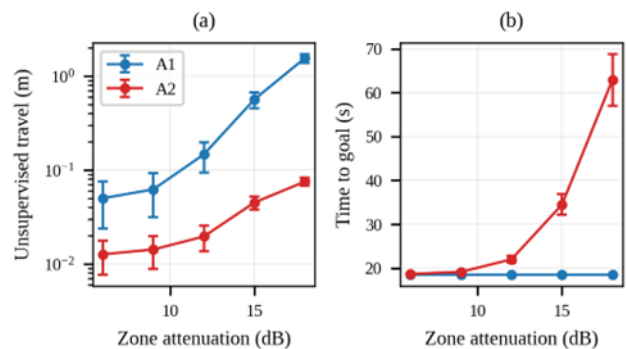


Fig. 5. Sensitivity to zone attenuation: (a) unsupervised travel, (b) time to goal (mean and 95% CI).

D. Failsafe Timeout (E5)

With an abrupt outage at 75% speed, the stopping distance measured from outage onset rose from 0.22 m at $T_{to} = 0.2$ s to

0.68 m at 1.0 s, whereas the false-stop rate under the burst-interference stress test fell from 9.2 to 0.8 stops per minute (Fig. 6). The default $T_{to} = 0.5$ s gives 0.45 m and 3.7 false stops per minute. Without the failsafe, A0 and A1 covered 3.8 m and 4.6 m in the 6 s after outage onset. Timeouts of 1.0 s and 1.5 s give identical results because, with $T_{hb} = 1$ s, the heartbeat term drives the CQI to the critical level at about 1 s regardless. The false-stop figures depend entirely on the assumed burst process (0.25 bursts/s, 0.35 s mean duration, 25 dB) and are a stress-test measure, not a field estimate.

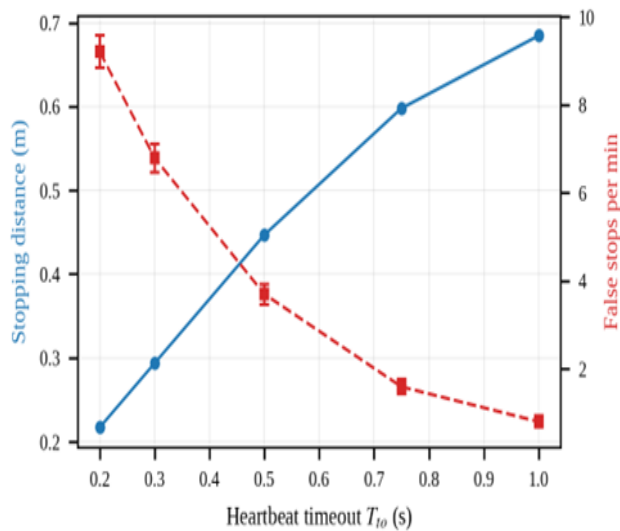


Fig. 6. Stopping distance (left axis) and false-stop rate (right axis) versus heartbeat timeout.

E. Obstacle Safety (E6)

Without an obstacle term, collisions grew with speed (Table VI, Fig. 7): 16% at 75% and 50% at 100% speed for A1/A2. A3/A4 recorded no collisions in any condition (Fisher $p = 1.6 \times 10^{-5}$ at 75% and 4.4×10^{-19} at 100%), with final clearance of 0.22 m and 0.17 m against the 0.15 m design margin. A0 collided less than A1 at 75% speed only because it actually drives slower than commanded. These rates are conditional on the assumed operator reaction model.

TABLE VI
COLLISION RATE (%) VERSUS COMMANDED SPEED

Config.	25%	50%	75%	100%
A0	0	0	0	38
A1 / A2	0	0	16	50
A3 / A4	0	0	0	0

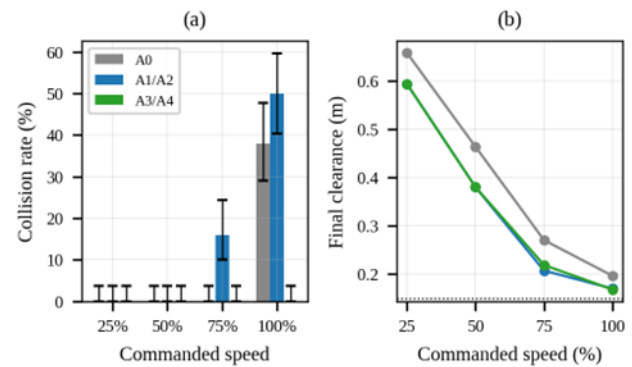


Fig. 7. (a) Collision rate with Wilson 95% intervals; (b) final clearance in runs without collision (dotted: 0.15 m margin).

F. Energy per Metre and Stall Fault (E7, E9)

Energy per metre is a shallow U-shaped function of speed (Fig. 8). At 0.2 m/s it is 2.57 J/m, falling to a minimum of 1.61 J/m near 0.81 m/s and rising slightly toward full speed. The 0.30 W electronics load dominates at low speed, which is why slowing the robot down does not save energy per metre in this model and explains the energy penalty of Section V-C. In the stall test, A0 consumed 9.1 J over the 3 s stall, A1–A3 30.0 J (the PI loop saturates the duty cycle) and A4 4.0 J, because the power monitor latched a fault after 0.35 s, a 87% reduction relative to A1.

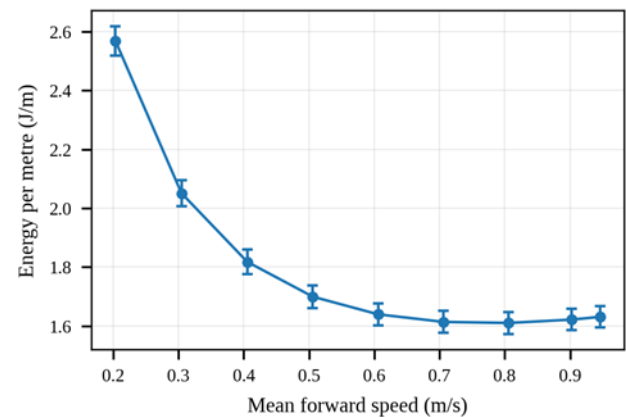


Fig. 8. Energy per metre versus mean speed for A1 over 10 m (mean and 95% CI, 30 trials).

G. Ablation Summary (E8)

TABLE VII
ABLATION SUMMARY

Metric	A0	A1	A2	A3	A4
Tracking MAE, 52.2 75% (RPM)		0.8	0.8	0.8	0.8
Unsup. travel (m)	0.255	0.228	0.025	0.025	0.025
Mission time (s)	21.9	18.5	22.8	22.8	22.8

Metric	A0	A1	A2	A3	A4
Mission energy (J/m)	1.60	1.58	1.69	1.69	1.69
Collisions, 100% (%)	38	50	50	0	0
Stall energy (J)	9.1	30.0	30.0	30.0	4.0

Each feature improves the metric it targets: PI control (tracking), CQI/failsafe (unsupervised travel), obstacle limit (collisions), power monitor (stall energy). The CQI feature alone costs mission time and energy.

Table VIII summarises how each limitation of the previous open-loop robot (A0) is rectified and the simulation evidence for it.

TABLE VIII
RECTIFICATION OF THE PREVIOUS SYSTEM'S PROBLEMS

Problem in A0	Rectification	Simulation evidence
Speed error from friction, load and battery sag	Encoder PI loop (A1)	MAE at 75%: 52.2 → 0.81 RPM
Heading drift from wheel mismatch	Per-wheel PI (A1)	Drift: 42% → 3.8% of path
Keeps driving after link loss	CQI limit + heartbeat failsafe (A2)	Travel in 6 s after outage: 3.8 m (A0) → 0.45 m; unsupervised travel 0.255 → 0.025 m
No obstacle protection	Stopping-distance limit (A3)	Collisions at 100% speed: 38% → 0%
Stall wastes energy	Current monitor with fault latch (A4)	Stall energy: 9.1 → 4.0 J

VI. DISCUSSION

The ablation attributes each improvement to one feature. Encoder feedback is responsible for essentially all of the tracking and drift gain, and it also enables the other features by making commanded speed meaningful. CQI adaptation and the heartbeat failsafe are what bound unsupervised travel and the stopping distance after link loss; the obstacle term is what removes collisions that depend on the operator, and the power monitor limits energy wasted in a stall. None of the features helps the others' metrics in this model, so each is justified by the hazard it covers rather than by a general performance gain.

The trade-offs are the main finding. CQI adaptation lengthened the mission and raised energy per metre, and under

severe attenuation it can leave the robot waiting for a link that does not recover, so a deployed system needs a policy for a prolonged outage (for example, return along the path or wait for the operator). A timeout of 0.5–0.75 s balanced stopping distance and false stops in the stress test. For energy, the model suggests operating near 60–80% of maximum speed; below 40% the fixed electronics load dominates and energy per metre rises sharply.

VII. LIMITATIONS AND THREATS TO VALIDITY

All results are simulated. The model parameters are representative of a small gear-motor robot but are not measurements of the prototype, and absolute numbers (MAE, distances, joules) will differ on hardware. In particular the simulated encoder has no noise beyond quantisation, there is no wheel slip, backlash or sensor dropout, and the BLE model is a generic log-distance, shadowing and burst model rather than a measured trace; phone chipset and operating system are known to change BLE behaviour [11]. The operator reaction model and the obstructed-zone geometry are assumptions and drive the collision and mission results. Burst statistics determine the false-stop rates. The study covers a single robot with a local BLE link and does not address multi-robot planning or radio-map prediction [1]–[4]. A0 is simulated on the same BLE model as the other configurations, so it does not represent the HC-05 Bluetooth Classic link of the original robot.

Hardware validation. The same experiments (E1–E9) can be repeated on the prototype by logging, at 20 Hz, timestamp, configuration, target and measured RPM, duty, CQI, packet sequence and loss, supply voltage and current, and range, as CSV. The CQI thresholds, PI gains and T_{io} should be recalibrated from those logs, and the simulation parameters updated, before any quantitative claim is made about the physical robot.

CONCLUSION

A lightweight communication-aware speed controller for a low-cost BLE robot was designed and verified by Monte-Carlo simulation. In the model, encoder-based PI control brought speed error from tens of RPM to under 1 RPM; CQI-based speed limiting with a heartbeat failsafe cut unsupervised travel by 89% in a degraded-link mission at a cost of 24% mission time and 7% energy per metre; an obstacle-aware limit removed operator-dependent collisions; and power monitoring cut stall energy by 87%. The study quantifies the

trade-offs of each feature and identifies an operating region (timeout 0.5–0.75 s, speed 60–80% of maximum) that balances safety and energy. The findings are simulation-based and should be confirmed on hardware.

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