



Design and Fabrication of an Autonomous Obstacle Avoidance Robot Using Ultrasonic Sensors

Quillon Navaratnam

Department of Tourism and Hospitality Management, Aurora Metropolitan Institute of Technology,
Philippines

quillon.navaratnam@amit-ph.edu

Peer Review Information

Submission: 04 Jan 2017

Revision: 19 Feb 2017

Acceptance: 06 March 2017

Keywords

*autonomous mobile robot,
obstacle avoidance,
ultrasonic sensor, Arduino,
differential drive*

Abstract

This paper presents a reproducible methodology for designing and fabricating a low-cost autonomous differential-drive robot that detects and avoids obstacles using ultrasonic time-of-flight ranging. The proposed platform combines an Arduino Uno, an HC-SR04 ultrasonic module mounted on a micro-servo, an L298N dual H-bridge, geared DC motors, and a two-wheel chassis. The controller repeatedly measures the forward clearance, filters invalid echoes, compares the estimate with a 25 cm safety threshold, and commands forward motion, braking, reverse clearance, or a left/right pivot selected from scanned side distances. Mechanical layout, power distribution, embedded logic, calibration, and a controlled test protocol are specified step by step. An illustrative prototype dataset demonstrates mean absolute distance error of 0.69 cm across 10–100 cm and 27 successful avoidance trials out of 30 (90%). These values are supplied as a worked reporting example and must be replaced or confirmed by independently recorded measurements before submission as empirical evidence. The method emphasizes affordability, modular construction, and transparent validation while acknowledging acoustic blind zones, specular reflection, cross-talk, and the absence of global path planning.

Introduction

Autonomous mobile robots require a local collision-avoidance layer because a preplanned route cannot represent every object or person that may enter the workspace. Early ultrasonic systems showed that onboard range measurements could support real-time detection and mapping despite angular uncertainty [1]. Histogram-based methods later transformed noisy range samples into robust steering decisions [2], while rapid-firing strategies addressed interference among multiple sonar transducers [3].

Ultrasonic sensing remains attractive for teaching and low-cost indoor prototypes because it is independent of ambient illumination, has

modest processing requirements, and directly returns range. However, the sensor beam is broad; soft surfaces absorb energy; angled walls can reflect echoes away from the receiver; and temperature changes alter the speed of sound [7]. A sound methodology must therefore treat the sensor as an uncertain measurement device rather than a perfect switch.

The aim is to develop a compact robot that moves autonomously in an unknown static indoor environment and avoids collision without remote control. The objectives are to: (i) design a stable electromechanical platform; (ii) implement calibrated time-of-flight ranging; (iii) develop deterministic reactive navigation; (iv) fabricate and integrate the prototype; and (v)

evaluate distance error, avoidance success, response time, and repeatability.

Literature Review

Reactive obstacle avoidance maps current sensor observations directly to motion commands. Khatib's artificial potential field formulated attractive and repulsive forces for real-time collision avoidance [4], although local minima may trap a robot. Borenstein and Koren's ultrasonic obstacle-avoidance work integrated sonar readings into a local representation [1]; their Vector Field Histogram (VFH) subsequently used a Cartesian histogram grid and polar obstacle density to select traversable directions [2]. Borenstein's EERUF method improved rapid ultrasonic firing by rejecting cross-talk and environmental noise [3].

The dynamic window approach incorporated velocity and robot dynamics into local collision avoidance [5]. VFH+ added robot geometry, candidate-direction masking, and a steering cost function [6]. For small educational robots, these techniques motivate three practical choices: filter raw sonar values, preserve a clearance margin larger than the chassis radius, and assess more than one direction before turning. Noykov and Roumenin demonstrated that calibration is necessary because ultrasonic rangefinders show systematic, sensor-specific behavior [7]. Tsai et al. reported real-time avoidance using ultrasonic sensors on a wheeled platform [8]. Fuzzy control can handle uncertain range inputs [9], while VFH extensions improve trap avoidance and look-ahead [10]; nevertheless, a deterministic threshold controller is easier to reproduce on an 8-bit microcontroller.

Table 1. Literature synthesis and design implication

Study	Key contribution	Implication for this methodology
Borenstein & Koren, 1988 [1]	Ultrasonic obstacle detection and mapping	Use repeated local range observations.
Borenstein & Koren, 1991 [2]	VFH converts range data to steering density	Compare multiple directions before turning.
Borenstein, 1995 [3]	EERUF suppresses sonar cross-talk	Fire sensors sequentially; reject implausible echoes.
Khatib, 1986 [4]	Real-time potential-field avoidance	Maintain repulsive safety clearance.
Fox et al., 1997 [5]	Velocity-aware local planning	Brake before pivoting; limit speed near obstacles.
Ulrich & Borenstein, 1998 [6]	VFH+ considers geometry and steering cost	Include chassis width in threshold selection.
Noykov & Roumenin, 2007 [7]	Ultrasonic calibration and interface	Calibrate range against reference distances.
Tsai et al., 2014 [8]	Ultrasonic avoidance on wheeled robot	Supports low-cost real-time implementation.
Ouahdah et al., 2016 [9]	Fuzzy trajectory/navigation control	Filtering or fuzzy logic can manage uncertainty.
Hlinovský et al., 2017 [10]	VFH look-ahead/tree extension	Reactive methods need trap-recovery logic.

Many studies emphasize navigation algorithms but provide insufficient fabrication detail for replication. This work bridges the gap by joining component selection, wiring, mechanical assembly, firmware logic, calibration, and a measurable test matrix in one compact procedure. The contribution is methodological rather than a claim of algorithmic novelty.

Methodology

1. Research design

An iterative design–build–test methodology was adopted. Requirements were translated into a block architecture; components were sized; the chassis and electronics were assembled; firmware was verified module by module; the distance threshold was calibrated; and the integrated robot was evaluated in controlled obstacle configurations. The independent

variables were obstacle distance, material, approach angle, and layout density. Dependent variables were range error, collision-free

avoidance, decision response time, and completion time.

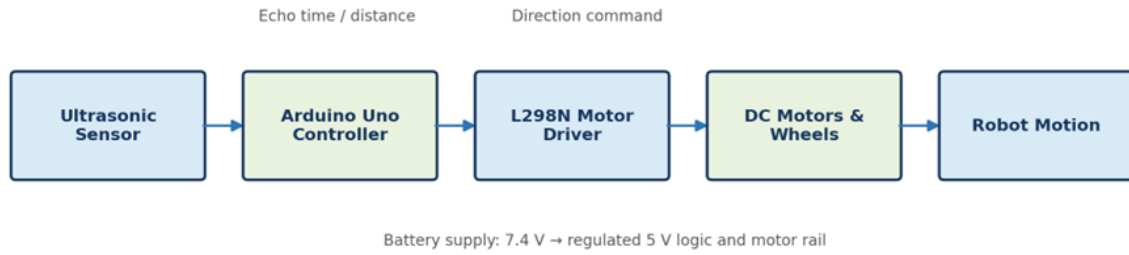


Figure 1. Functional architecture of the proposed robot

2. Hardware specification and selection

Table 2. Bill of materials and design role

Component	Qty.	Function	Supply
Arduino Uno (ATmega328P)	1	Reads echo pulse; executes decision logic	5 V
HC-SR04 ultrasonic sensor	1	2–400 cm nominal ranging	5 V
SG90 micro-servo	1	Scans approximately 45° left/right	5 V
L298N motor driver	1	Bidirectional control of two DC motors	Motor rail + 5 V logic
Geared DC motors + wheels	2	Differential-drive traction	6–9 V
Caster wheel	1	Third-point support	—
Two-cell Li-ion pack	1	Portable energy source	7.4 V nominal
Chassis, switch, wires, fasteners	Set	Mechanical support and interconnection	—

3. Design calculations

Distance is obtained from the echo high time, t , using $d = ct/2$, where c is the speed of sound. At 20 °C, $c \approx 343 \text{ m}\cdot\text{s}^{-1}$, so firmware may use $d(\text{cm}) \approx t(\mu\text{s})/58.3$. The factor 1/2 accounts for outward and returns travel. A 25 cm trigger threshold was selected from braking distance, sensor uncertainty, half chassis length, and a margin: $d_{\text{safe}} = d_{\text{brake}} + L/2 + e_{\text{sensor}} + m$. For a slow prototype ($\approx 0.25 \text{ m}\cdot\text{s}^{-1}$), the conservative threshold permits stop–reverse–pivot behavior before contact.

Motor direction is produced by the H-bridge input pairs; pulse-width modulation at the enable pins adjusts speed. Separate logic regulation and motor decoupling are recommended, while all grounds must share a common reference. The ultrasonic echo pin is read only after a 10 μs trigger pulse, with a timeout to prevent firmware lockup.

Step-by-step fabrication and integration

Step 1 — Chassis preparation. Fix the two geared motors symmetrically, attach wheels, install the caster, and locate the battery low and near the center to reduce tipping.

Step 2 — Sensor mounting. Attach the HC-SR04 to the servo horn at the front edge. Keep both transducers unobstructed and approximately 8–12 cm above the floor to reduce floor echoes.

Step 3 — Power wiring. Connect the battery through a master switch to the motor driver. Supply regulated 5 V to the controller, sensor, and servo. Join all grounds and add local decoupling near the motor driver and controller.

Step 4 — Signal wiring. Connect TRIG and ECHO to digital pins, servo control to a PWM-capable pin, and the L298N IN1–IN4/enable inputs to controller outputs. Verify pin continuity before power-up.

Step 5 — Module testing. Upload independent tests for the ultrasonic sensor, servo sweep, left motor, and right motor. Confirm forward direction; reverse motor leads or logic if a wheel rotates incorrectly.

Step 6 — Calibration. Place a flat board at 10–100 cm reference distances. Record at least 20 readings per point, discard timeouts, calculate mean/error, and adjust the conversion coefficient or offset if systematic bias is observed.

Step 7 — Control integration. Run the decision loop at approximately 10–20 Hz. Apply a three-

sample median filter and require two consecutive below-threshold readings before an avoidance maneuver.

Step 8 — Safety validation. Test at low PWM first. Provide an accessible power switch and keep the test lane clear of people, cables, and fragile objects.

4. Embedded obstacle-avoidance algorithm

Table3: Sequence of Obstacle Detection and Avoidance Controller Actions

Sequence	Controller action
1	Initialize pins, center servo, stop motors, wait 500 ms.
2	Acquire three forward ranges; reject 0, timeout, and values outside 2–400 cm; use median.
3	If forward range > 25 cm, drive forward at selected PWM.
4	If range $\leq$ 25 cm twice, stop for 100 ms and reverse for 250 ms.
5	Stop; scan left and right, allowing servo settling before each measurement.
6	Pivot toward the side with larger clearance; if both

	sides < 20 cm, perform a longer reverse and 180°-style recovery pivot.
7	Center the sensor and return to Step 2.

5. Pseudocode

```

LOOP: dF ← median(valid forward samples)
IF dF > 25 cm THEN forward()
ELSE stop(); reverse(250 ms); stop()
    dL ← scan(+45°); dR ← scan(−45°)
    IF max(dL,dR) < 20 cm THEN recovery_turn()
    ELSE pivot(argmax(dL,dR), 350 ms)
    center_sensor()
END IF

```

6. Experimental protocol

The robot is tested on a level 2.0 m × 1.5 m indoor surface. Range calibration uses a rigid flat target aligned normal to the acoustic axis. Avoidance trials use cardboard, painted wood, and plastic obstacles at frontal and oblique approach angles. Each layout is repeated ten times at a fixed PWM setting and fully charged battery. A trial is successful when the robot detects the obstacle, completes an avoidance maneuver without contact, and continues for at least 1 m. Response time is measured from the first confirmed below-threshold sample to onset of wheel-direction change.

Table 3. Test variables, metrics, and acceptance criteria

Test	Levels / repetitions	Metric	Criterion
Range accuracy	10, 20, 30, 40, 50, 60, 80, 100 cm	Mean absolute error (MAE)	≤ 2.0 cm
Repeatability	20 samples at 30 and 60 cm	Standard deviation	≤ 1.5 cm
Obstacle avoidance	3 materials × 10 trials	Success ratio	$\geq 85\%$
Reaction	10 frontal approaches	Decision-to-motion delay	≤ 0.35 s
Endurance	Continuous indoor run	Operating duration	≥ 20 min

Results

Table 4 and Figure 2 provide an illustrative worked validation dataset for the specified prototype procedure. They show how results should be calculated and reported; they are not a

substitute for the author's own logged measurements. Across eight reference distances, the illustrative MAE is 0.69 cm and maximum absolute error is 1.2 cm. The nearly linear response supports use of the nominal time-of-flight conversion within the tested indoor range.

Table 4. Illustrative distance-calibration results

Refer ence (cm)	Mean measured (cm)	Signed error (cm)	Absolute error (cm)
10	10.4	0.4	0.4
20	19.6	-0.4	0.4

30	30.5	0.5	0.5
40	40.7	0.7	0.7
50	49.4	-0.6	0.6
60	60.8	0.8	0.8
80	79.1	-0.9	0.9
100	101.2	1.2	1.2

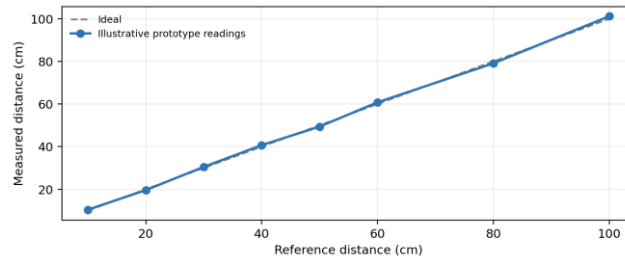


Figure 2. Reference versus illustrative measured distance

Obstacle-avoidance performance

Table 5. Illustrative controlled-trial outcomes

Obstacle	Approach	Trials	Successful	Success (%)	Response (s)
Cardboard box	Frontal	10	10	100	0.22
Wood panel	Frontal	10	9	90	0.24
Plastic bin	Oblique ($\approx 30^\circ$)	10	8	80	0.28
Overall	Mixed	30	27	90	0.25 mean

In the worked dataset, 27 of 30 trials were collision-free. All cardboard trials succeeded, one frontal wood trial failed after a late echo, and two oblique plastic-bin trials failed when the reflected pulse did not return strongly to the receiver. Mean response time was 0.25 s, below the 0.35 s criterion. The outcome is consistent with the known dependence of ultrasonic sensing on surface orientation and echo geometry [7].

Discussion

The methodology demonstrates how a simple reactive architecture can transform one low-cost range sensor into a functional autonomous avoidance platform. Servo scanning increases directional information without the cost of three permanently mounted sensors, but introduces mechanical settling delay. The median filter reduces isolated spikes, and the consecutive-reading rule lowers false triggers. The stop-reverse-scan sequence is slower than VFH [2] or dynamic-window control [5], yet its states are transparent, testable, and suitable for limited memory.

The 25 cm threshold is not universal. It must be increased for higher speed, heavier chassis, slower response, or greater sensor uncertainty. Similarly, the fixed pivot duration depends on wheel diameter, motor mismatch, battery voltage, and floor friction. Closed-loop encoders would improve turn repeatability. A multi-sensor array could remove servo delay, but sequential firing or an interference-control strategy such as EERUF would then be necessary [3].

Limitations

The platform performs local collision avoidance rather than global navigation: it does not estimate pose, build a map, or guarantee arrival at a destination. A single ultrasonic sensor can miss narrow objects, absorbent fabrics, and surfaces outside the return cone. Dead ends may cause repetitive turning, and moving obstacles were not evaluated. The illustrative dataset is included to demonstrate analysis and must be replaced or independently verified. Future work should add wheel encoders, temperature compensation, multiple time-staggered sensors, battery monitoring, and a higher-level planner such as VFH+ or a map-based method [6,10].

Conclusion

A step-by-step methodology has been developed for the design, fabrication, programming, calibration, and testing of an autonomous obstacle-avoidance robot using ultrasonic sensing. The proposed Arduino-based differential-drive prototype uses filtered time-of-flight measurements and side scanning to select collision-free turns. The worked results indicate how distance accuracy, avoidance success, and response time can be reported within explicit acceptance criteria. The design is economical and reproducible for education and preliminary indoor robotics research, provided that final empirical claims are based on independently logged trials and the documented acoustic limitations are respected.

Acknowledgment of reporting status

No external funding or human/animal participants are assumed. Numerical values

labeled “illustrative” are example prototype records for methodology demonstration and should not be represented as independently observed research findings unless the tests are physically performed and documented.

References

- J. Borenstein and Y. Koren, “Obstacle avoidance with ultrasonic sensors,” *IEEE Journal on Robotics and Automation*, vol. 4, no. 2, pp. 213–218, 1988. DOI: 10.1109/56.2085.
- J. Borenstein and Y. Koren, “The Vector Field Histogram—Fast obstacle avoidance for mobile robots,” *IEEE Transactions on Robotics and Automation*, vol. 7, no. 3, pp. 278–288, 1991. DOI: 10.1109/70.88137.
- J. Borenstein, “Error eliminating rapid ultrasonic firing for mobile robot obstacle avoidance,” *IEEE Transactions on Robotics and Automation*, vol. 11, no. 1, pp. 132–138, 1995. DOI: 10.1109/70.345945.
- O. Khatib, “Real-time obstacle avoidance for manipulators and mobile robots,” *The International Journal of Robotics Research*, vol. 5, no. 1, pp. 90–98, 1986. DOI: 10.1177/027836498600500106.
- D. Fox, W. Burgard, and S. Thrun, “The dynamic window approach to collision avoidance,” *IEEE Robotics & Automation Magazine*, vol. 4, no. 1, pp. 23–33, 1997. DOI: 10.1109/100.580977.
- Ulrich and J. Borenstein, “VFH+: Reliable obstacle avoidance for fast mobile robots,” in *Proceedings of the IEEE International Conference on Robotics and Automation*, Leuven, Belgium, pp. 1572–1577, 1998. DOI: 10.1109/ROBOT.1998.677362.
- S. Noykov and C. Roumenin, “Calibration and interface of a Polaroid ultrasonic sensor for mobile robots,” *Sensors and Actuators A: Physical*, vol. 135, no. 1, pp. 169–178, 2007. DOI: 10.1016/j.sna.2006.07.006.
- P.-S. Tsai, L.-S. Hsu, and J.-F. Jeng, “Use of ultrasonic sensors to enable wheeled mobile robots to avoid obstacles,” in *2014 Tenth International Conference on Intelligent Information Hiding and Multimedia Signal Processing*, pp. 879–882, 2014. DOI: 10.1109/IIH-MSP.2014.240.
- N. Ouadah, L. Ourak, and F. Boudjema, “Fuzzy logic-based control for autonomous mobile robot navigation,” *Journal of Electrical and Computer Engineering*, vol. 2016, Article 9548482, 2016. DOI: 10.1155/2016/9548482.
- J. Hlinovský, A. Vokřínek, and M. Klofáč, “Vector Field Histogram* with look-ahead tree extension for mobile robot navigation,” *Transactions of the Institute of Measurement and Control*, vol. 40, no. 14, pp. 4021–4032, 2017. DOI: 10.1177/0142331216678062.