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Design and Implementation of a Multi-Modal Wireless Robotic System for Smart Vehicle Navigation

Chaitanya Pilane, Dhanashri Pawar, Mansi Patekari, Lakshaya Pillai, Milind Patil
Department of Electronics and Telecommunication Engineering Vishwakarma Institute of Technology, Pune, Maharashtra, India

Abstract— This paper describes the design and development of a multi-modal wireless robotic system for the robotic vehicle that can be controlled manually by Bluetooth, voice, and navigation by gestures. In this, the Arduino is the center of the controlling unit that combines the communication and sensing modules. There is an HC-05 Bluetooth module that allows manual and voice commands by the smartphone app. In controllinggestures,itusesanaccelerometer-gyroscopesensor, an MPU-6050 module, where a reliable means of wireless data transfer is done using RF transceivers, nRF24L01. In motor control, it uses an L298N motor driver and DC motors. For safety reasons, an ultrasonic sensor is employed for real-time obstacle detection. On detection of an obstacle within a fixed distance,thevehicleautomaticallystopstoavoidcollisions.The results demonstrate that there is stable communication, good controlresponse,efficientobstacleavoidance,andsmoothmode switching. The new system provides enhanced flexibility and convenience and can be applied to educational robots, mobility aids, and surveillance systems.

Keywords—Arduino,Bluetoothwirelesscommunication,gesture- controlled system, voice-controlled system, robotic vehicle, ultrasonic sensor, obstacle detection, wireless robotic system

I. INTRODUCTION

Inthelasttwodecades,interestinroboticvehicleshasgrown due to a variety of applications in industrial automation, military, healthcare, surveillance, and assistive mobility. Remote operation allows robotic systems to work in hazardous, inaccessible, or precision demanding environments while improving user safety. Besides flexible mechanisms for control, safety-related features such as real-time obstacle detection are crucial for efficient robotic operation, especially in dynamic and unpredictable environments.Amongseveralsensingtechniques,ultrasonic sensors have been one of the widely adopted solutions for short-range obstacle detection due to their simplicity andefficacy. Conventional control of robotic vehicles has been developedintheframeworkofsingle-modecontrolsystems, suchaswiredcontrollers,wirelesshandhelddevices,orfixed control terminals. While functional, these methods usually sharesomeseriousdrawbacks:notably,restrictedflexibilityand decreased user engagement. Given recent advances in human-machine interaction and wireless communication technologies, there is a growing need for intelligent robotic platformsthatcansupportmultiplecontrolmodeswithinone unifiedsystemarchitecture.Thisresearchworkisdevotedto thedesignanddevelopmentofamulti-modalroboticvehicle control system that supports three complementary modes of operation: Bluetooth-based manual control, voice command control, and gesture-based control. Bluetooth-based control allows users to intuitively operate manually using a smartphone application. Voice control enables hands-free manipulation, which is greatly important in the case of physicallydisabledusers.Gesture-basedcontrolembedsmore interactivitybytranslatinghandmovementthroughtheuseof an accelerometer and gyroscope sensor into directional motion commands. The Arduino microcontroller is being exploited for the implementation of the proposed system. Thiscontrollerhasmulti-communicationinterfacesonboard- such as HC-05 Bluetooth modules and nRF24L01 RF transceivers for gesture recognition-supported by an MPU6050sensor.Inthis,themotoractuationisgivenbythe L298N motor driver, and UART, I2C, and SPI protocols providesupporttocommunicateamongsystemcomponents. Multi-protocol integration allows coordinating heterogeneous hardware components in this environment with much efficiency. Apart from multi-modal control, the system integratesanultrasonicsensorthatcontinuouslymonitorsany obstaclesalongthepathofthevehicle.Ifthereisdetectionof an obstacle inside a threshold distance predefined, it automatically stops the vehicle and hence supports collision avoidanceandimprovessafetyinitsoperationalcapabilities. Thiscapabilityrunsacrossallcontrolmodesandenhancesthe system'spracticalapplicabilityinreal-worldsettingsofindoor navigation, monitoring, and also assistive robotics.

While different robotic control systems using Bluetooth, voice, or gesture inputs are reported in the literature, most of the existingsolutionsfocusonsingle-modeoperationanddonot allow seamless integration of multiple techniques within a unified platform. Furthermore, the literature has paid little attentionsofartotheissuesofautomaticmodeswitchingand coherentsafetyenforcementacrossthevariousmodesof control.Majorcontributionsinthisworkareasfollows: A unified multi-modal robotic control system, comprising designandimplementation,thatusesBluetooth-basedmanual control, voice commands, and gesture-based navigation.

- Seamlessly and automatically switching between different controlmodeswithoutmanualintervention.Theintegrationof different wireless communication protocols over a compact, low-cost robotic platform.
- Obstacledetectionmechanismbasedon anultrasonic sensor operationalthroughoutallthecontrolmodes.Thisisaimedat thedesignanddevelopmentofmodularand extensiblerobot architecture for assistive, educational, surveillance, and automation tasks.

II. LITERATURE REVIEW

Owing to the flexibility and ease with which they are implemented, wirelesscontrolmechanismsformobilerobotic systems have become popular topics in the literature. In this regard,Bluetooth-basedroboticcontrolsystemshavealready beenshownsuitablefor low-power,shortrangeapplications; however, it has also been reported that besides the restricted operating range, the key drawbacks include signal instability[1].Human–robotinteractionstudiesdevelopedso far suggest that, for real-world deployment of a robotic system, its control interface should ideally be intuitive and user-friendly,especiallybecauseenvironmentalandusability constraints play a vital role in such processes[2]. To address these challenges, multi-modal robotic control systems based on various input techniques have been proposed. Gesture- basedroboticcontrolhasgainedconsiderableattentiondueto its natural and interactive mode of navigating motions[3]. Studies using motion sensors like the MPU6050 have demonstrated effective recognition of hand gestures for directional control of robotic vehicles [4]. Real-time interpretationofthetiltanglesofthehandusingaccelerometer and gyroscope data has been shown to improve responsiveness and control accuracy [5]. Comparative analyses between gesture-based autonomous and hybrid systems show that multi-modal approaches offer greater flexibility and improved user interaction [6].

The robotic system of voice control has been extensively investigated for hands-free operations, especially in the applications of assistive mobility. Various voice command- based navigations were possible using smartphone applicationsandBluetoothcommunications[7].Withhigher- orderimprovementsinspeechrecognitionalgorithms,voice- controlled robotic systems are becoming more feasible for practical applications because of their higher command accuracyandsystemreliability[8].Ontheotherhand,voice- based control alone may show performance degradation in noisy environments, thus necessitating alternative or complementarycontrolmodes.Inordertoeliminatetherange limitations linked with the Bluetooth-based systems, some researchers focused on investigating the integration of RF communication modules. Consequently, some studies highlighted that the integration of Bluetooth and RF communications improves the operational range and the communication reliability [9]. To enhance the navigation stabilityandoverallperformanceofthesystems,theadaptive hybrid control systemsthat can switchdynamically between differentcontrolmodeshavebeenproposed[10].Moreover, theoptimizationoffilteringtechniquesandtheapplicationof sensorerrorcompensationmethodstotheinertial measurement units provided an improved accuracy in recognizing gestures [11].

RF-basedmultimoderoboticsystemsprovidehighreliability andfasterresponsetimes,especiallyinopenandlong-distance environments [12]. Low-power RF transceivers like the nRF24L01modulehavebeensingledoutasefficientsolutions for energy-efficient long-range wireless communication in mobile robotics [13]. Motor driver modules like the L298N arewidelyusedinordertoprovidestablecurrentcontroland reliable bidirectional motor operation in robotic platforms [14].Recent survey studies indicate a growing trend toward integrating multiple controlmodalities, including Bluetooth, voice, gesture, and sensor-based safety mechanisms, to enhance robustness, user comfort, and system intelligence [15]. Modular and dynamically adaptable robotic architectures have been emphasized as essential for supporting multi-modal interaction in practical applications [16].Moreover,naturalandflexibleuserinterfacesareviewed as key success factors in human–robot interaction within dynamicoperationalenvironments[17].Sensor-basedsafety systems, especially ultrasonic sensing, have been widely adopted for short-range obstacle detection and collision avoidance [18]. While these efforts constitute important progress, most existing systems focus on individual control modes or lack seamless integration of multiple control techniques within a unified platform. This work addresses theselimitationsbypresentingaunifiedmulti-modalrobotic control system that integrates Bluetooth, voice, and gesture-based control with consistent safety enforcement.

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III. METHODOLOGY

In the proposed system, the method employed emphasizes buildinganautonomousroboticcarthatcanbecontrolledby three different techniques: manual control using Bluetooth technology,voice commands,andgesturecontrol technology. In this system, control signals are processed by an Arduino Uno microcontroller, which acts as the main CPU in the system by interpreting commands and making necessary decisionsregardingmotormovement.Inmanuallyandvoice- controlled systems, an Android smartphone is used, while gesturerecognitionisdoneusinganMPU6050gyroscopeand accelerometer module, and wireless transmission is done usingnRF24L01radiomodules.Itconstantlyobservesallthe input channels and performs the first valid command that enables automatic switching and increases the flexibility of operation.Furthermore,theultrasonicsensorisimplemented on the receiver side for real-time obstacle detection and safe operation for all control methods. The workflow of the proposed system is shown below in Figure 3.

1) Receiver-Side System Architecture: The design of the receiver-sidesystemarchitecturewillincorporatecomponents mountedontheroboticvehicletoreceivecontrolcommands and perform motion. This will include an Arduino Uno microcontroller board, an HC-05 Bluetooth module, an nRF24L01RFreceiver,anultrasonicsensor,anL298Nmotor driver, DCmotors, andarechargeablebattery.Thehardware architectureforthereceiver-sidesystemwillappearasFig.1. In the figure according to transmitter or app command the L298 get PWM signals.
2) System Power Initialization: In this system, a 12 V rechargeablebatteryisutilizedasthemajorsourceofpower. This battery powers the Arduino Uno board, which is responsibleforcontrollingthespecifiedvoltagelevelsinall the modules connected to the system. When the system is turned on, the microcontroller begins processing by initializing the serial communication, sensor calibration, motor driver setup, and system standby state configuration.
3) Bluetooth Connectivity Establishment: The HC-05 Bluetooth module is capable of communicating with the Android smartphone by utilizing the UART communication processatabaudrateof9600.Thecontrolcommandsaresent to the Android smartphone, which in turn sends them to the robot by utilizing predefined characters such as F to move forward,Btomovebackward,Ltomovetotheleft,Rtomove to the right, and S to stop.
4) Voice Command Control: The voice command control system is implemented by making use of the built-in voice recognition system that is present in a smartphone. This system translatesvoice commandsinto textsand sendsthem to the robotic car through a HC-05 Bluetooth module. The systemisalternativelyusedwhenonewantstocontrolthecar while his or her hands are occupied. The system works properly when used in a noise-free environment.
5) Gesture-Based Transmitter Unit: The gesture-controlled subsystem includes a distinct transmitter component where the hand movement data is processed and transmitted wirelessly to the robotic vehicle for the execution of control commands.Thehardwarecomponentsforthetransmitterare depicted in Fig. 2 below.
6) Gesture Sensor Calibration & Processing: The MPU6050 sensor has a three-axis accelerometer and a three-axis gyroscope, which detects hand motion and direction. The accelerometersenseslinearacceleration,whilethegyroscope ismeasuring the angularvelocity. The datafrom the sensors is interpreted by the Arduino, and tilt angles are calculated, resulting in the predefined commands necessary for the movement of a road vehicle.
7) Wireless Gesture Transmission: The processed gesture commands are transmitted from the transmitter unit to the robotic vehicle through nRF24L01 wireless transceiver modules. The wireless communication method of gesture control is superior to the Bluetooth communication method becauseofenhancedrobustnessandrangeofwirelessgesture control.
8) Command Interpretation by Arduino: This is because the Arduino is constantly monitoring all incoming commands comingfromtheBluetoothmanualcontrolsystem,Bluetooth voice commands, and RF-based gesture commands. This is becauseassoonasitreceivesthefirstcommand,itactson it withoutdelay.
9) ObstacleDetectionandSafetyControl:Inthisprocess,an ultrasonic sensor isconnected to theArduino tomeasure the distancecontinuouslybetweentheroboticcarandthenearby obstacle. If any obstacle comes within a fixed threshold distance range, the Arduino will override the control signal
10) The ultrasonic sensor calculates distance using the time-of-flight principle: and send a stop signal to the motor driver.
11) Motor Control and Motor Action: The command for controlofmovementanddirectionandspeedofthecommand aswellwillbesenttotheL298Nmotordrivemodulefromthe ArduinoboardtocontroltheDCmotorsaccordingly.Assoon as thestopcommandisproduced, themotoroperationceases.
12) Continuous Operation Loop: The robotic car, after the executionofacommand,keepsmovinginthedesireddirection until another command is sent. When in gesture command mode, the car keeps moving if the user holds the respective hand position, thus allowing real-time control. WhenusingtheBluetoothorvoicecommandmode,itmoves until a command for stop or change in

direction is given

13) Mode Switching Flexibility: The Arduino is constantly observingallthecontrolchannelsandswitchingautomatically tothelastvalidinput.Forexample,iftheprojectisrunningin theGesturemodeandthereisaninputfromtheBluetooth,the projectimmediatelyswitchestotheBluetoothmode.Suchan aspect creates an easy and friendly interface for the users.
14) SystemShutdown:Uponreceiptoftheshutdownsignalor when the battery voltage becomes unsafe, the machine turns off all motor function and keeps non-essential subsystems from operating. Meanwhile, this shutdown process prevents thepossibilityofmachineoverheatingandbatterycelldamage by any unexpected mechanical movement of the machine.

A. *Mathematical Modelling*

1) To analytically describe the behavior of the proposed multi-modal robotic system, mathematical models for motion control, sensing, gesture interpretation, and system delay are formulated below.

Differential Drive Motion Model

The robotic vehicle is based on a differential drive mechanism with two independently driven wheels.

Let:

- V_L= Left wheel velocity
- V_R= Right wheel velocity
- L= Distance between wheels
- θ= Orientation angle
- (x, y)= Robot position

The linear velocity of the robot is:

$$V = \frac{V_R + V_L}{2} \quad (1)$$

The angular velocity is:

$$\omega = \frac{V_R - V_L}{L} \quad (2)$$

The position of the robot in a 2D plane is governed by:

$$\frac{dx}{dt} = V\cos\theta \quad (3)$$

$$\frac{dy}{dt} = V\ \sin\theta \quad (4)$$

$$\frac{d\theta}{dt} = \omega \quad (5)$$

These equations define the trajectory and orientation of the robotic vehicle.

2) *Ultrasonic Obstacle Detection Model*

The ultrasonic sensor calculates distance using the time-of-flight principle:

$$D = \frac{v.t}{2} \quad (6)$$

Where:

- D= Distance to obstacle
- v= Speed of sound (343 m/s)
- t= Echo return time

For collision avoidance:

If $D > D_{th}$ Motor Output=0 (7)

This overrides all control commands and ensures safety.

3) *Gesture Angle Computation Model*

The MPU6050 sensor provides acceleration values:

ax,ay,az

Tilt angles are calculated as:

$$\theta x = \tan^{-1}(\frac{a_y}{a_z}) \quad (8)$$

$$\theta y = \tan^{-1}(\frac{-a_x}{\sqrt{a_y^2+a_z^2}}) \quad (9)$$

Gesture commands are generated based on threshold comparison:

- $\theta_x > \theta_{th} \rightarrow$ Forward
- $\theta_x < -\theta_{th} \rightarrow$ Backward
- $\theta_y > \theta_{th} \rightarrow$ Right
- $\theta_y < -\theta_{th} \rightarrow$ Left

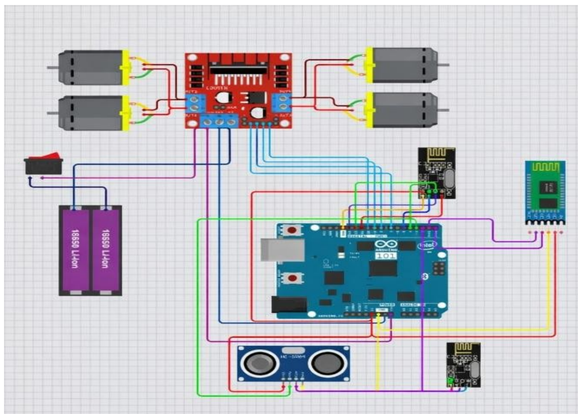

Fig.1:Receiver-sidehardwarearchitectureoftheroboticvehicle

Fig. 1. Is Hardware architecture and wiring diagram of the transmittersideofproposedmulti-modalroboticsystem.The Arduino microcontroller is used for processing and control, handling data acquisition, decision-making, and actuator control.AnL298NDualH-Bridgemotordriveisconnectedto Arduinoforcontrollingfour DCmotors,makingitpossiblefor the robotic vehicle to move in both forward and reverse directions with varying speeds. For wireless communication with regard to manual control and voice control, an HC-05 Bluetooth module is connected to Arduino for transmitting controlcommandsfromasmartphoneapplication. Forcontrol throughhandgestures,anotherexternalMPU6050unitofthe accelerator and gyroscope sensor is used, and controlinformation is transferred to the robotic vehicle through nRF24L01 wireless RF modules. To improve safety and autonomous control, an ultrasonic sensor is placed on the vehicletomeasurecontinuouslythedistancetoobjectsaround it,providingreal-timefeedbackaboutcollisionavoidanceby halting motor operations if objects are detected within a predetermined range. The entire system is capable of being continuallysuppliedbyarechargeablebatterypack,providing arobustandconvenientmeansforsustainedoperationofthe roboticsystem

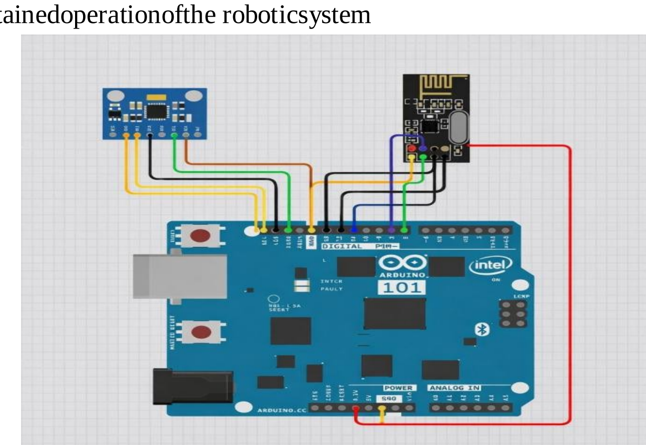

Fig.2:Transmitterhardwarearchitectureforgesture-basedcontrol

Fig. 2. Connection of the gesture control unit with the Arduinomicrocontroller.TheArduinomicrocontrollerboard servesasthemainprocessingelementandiscoupledwithan MPU6050 acceleration and gyro sensor, which uses the I²C communication interface to obtain real-time data about the motion and orientation of the human hand for gesture generation. The sensor is capable of detecting acceleration and rotation rates in three directions and sends these results tothemicrocontrollerforprocessingintogesturecommands for directional control of various robotic applications. The gesturecontrolunitcommunicateswithothercomponentsof the robotic vehicle wirelessly using an nRF24L01 wireless transceiver that is connected to the Arduino board using the SPIinterfaceforefficientwirelessdatatransfer.Itispowered throughtheregulatedsupply.Thissetupconstitutestheinput control unit of the multi-modal robotic framework

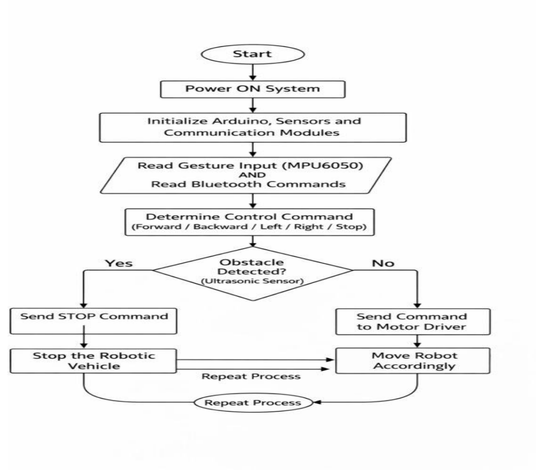

Fig.3:Overallworkflowoftheproposedmulti-modalrobotic control system

Fig.3.Flowchartoftheoperationallogicofthedesigned multi-modal robotic system. The sequence starts from turning on and initializing power, followed by initialization of the Arduino microcontroller, sensors, and wireless communication modules. The system is designed for continuous reading of gesture commands fromtheMPU6050sensorandreceptionofBluetooth- control commands from the user. On this basis, dependingonanalyzedinputs,thecontrolunitgenerates a particular motion command, such as “forward,” “backward,”“left,”“right,”or“stop.”However,priorto executingaparticular command,theultrasonic sensoris usedtocheckforanypossiblepresenceofanobstaclein the path of the vehicle. In both instances where an

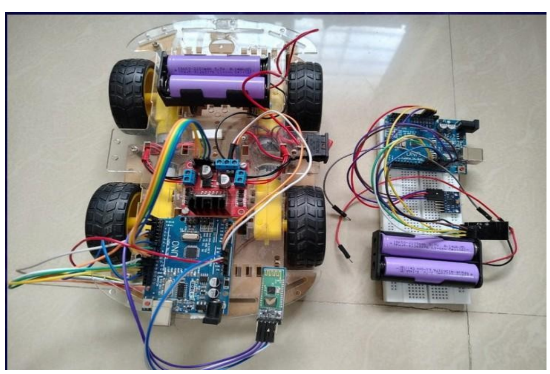

Fig.4:Actualprototypedeveloped duringthestudy

Thehardwareprototypeforthemulti-modalroboticvehicleis shown below in Figure 4. The vehicle is constructed using a differentialdrivesystem,propelledbyDCmotors,controlled by an L298Nmotorcontroller.Thebrainofthevehicleisan ArduinoUnocontroller,usedforeffectiveconnectiontoother devicessuchastheBluetoothmodule,usedforvoicecontrol, theRFmodule,usedforhandgesturingcontrol,aswellasan ultrasonicsensorforobstacledetection.Therobotisdrivenby rechargeable batteries, hence an example of a miniaturized design used for multi-modal wireless control.
usability. The designed multi-modal robotic vehicle is a reliable and economical solution for applications such as assistive mobility, surveillance, automation, and robotics education.

IV. RESULTS

The developed multi-modal robotic system was tested under indoor conditions to evaluate control accuracy, response time, communication range, and safety performance. The system operated successfully in all three control modes: Bluetooth, voice, and gesture.

Bluetooth control showed stable connectivity within approximately 10 meters and provided smooth directional movement with minimal delay. Voice control achieved high command recognition accuracy in low-noise environments, though slight performance reduction was observed under background noise. Gesture-based control allowed intuitive hand-driven navigation and demonstrated a larger communication range due to the RF module.

The ultrasonic sensor continuously monitored obstacle distance and successfully stopped the robot whenever an object entered the predefined safety range. This safety mechanism functioned effectively in all operating modes.

Overall, experimental observations confirm that the integrated multi-modal approach improves flexibility, usability, and operational reliability compared to single-moderobotic systems

ControlMode	Accuracy(%)	Delay(ms)	Range(m)	Safety	ObstacleDetection
BluetoothControl	98	80–100	~10	Yes	Yes
VoiceControl	92	150–200	~10	Yes	Yes
GestureControl	90	120–160	~25	Yes	Yes

Table1:PerformanceComparisonofControlModes

The findings support that a combination of several control methods into one system enhances malleability and ease of use over traditional systems, which support a single mode.

V. CONCLUSION

Inthissection,experimentalanalysisandresultsofintegrating the multi-modal robotic controlling system by using Bluetooth, Voice, and Gesture modes will be described. Figure4showsapracticalprototypedevelopedinthisstudy. Therobotsweretestedbymeansofar oboticcarcontrolledby threedifferentcontrolmethods.

Inthecontrolmodebasedon Bluetooth,thecommunicationofthesystemisstablewithina rangeofabout10m,withsmoothand accurate controlthrough a smartphone. Voice controlhadanaverage voicecommand recognitionaccuracyofaround92%inlow-noiseconditions, andtheperformancewasslightlyimpactedbythepresenceof background noise. The system of control by gestures, developedusing theMPU6050 sensorandannRF24L01 RF module, facilitated intuitive controlby tiltmotionsof hands, thoughsomein accuraciesoccurredduringfastmotionofthe

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