Design & Development of THE ROBUST – An Autonomous Mobile Robot

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***Abstract*—Autonomous mobile robots hold great worth in modern age. Application of such robots is not only limited to agricultural sector, sports, electric mobility, industry, military combats, and firefighting but they are also used to accomplish numerous critical objectives on the basis of installed payload(s). Ability to execute tasks independently makes them proficient to explore regions where hazards exist for mankind. A 4WD autonomous robot named "The ROBUST" was developed having capability of independent navigation to different locations while avoiding obstacles, ditches and steep slopes by sensing them remotely. System design and algorithms can be adopted or improved with addition of applicable payload(s) to produce innovative and application specific robots. Development of robots is based on different phases during which several complications are to be coped with. This article will facilitate readers to comprehend the design and development process of autonomous mobile robots in light of The ROBUST, emphasizing way of undertaking such projects systematically. Moreover, it describes the design constraints, experimental results and technical dilemmas that were experienced during system development.**

***Index Terms*—Artificial intelligence, autonomous mobile robots, obstacle avoidance, slope sensing.**

I. INTRODUCTION

MODERN technology is rapidly moving towards unmanned systems [1]. Fundamentals of autonomy are processors, sensors, actuators and intelligence algorithms. A processor serves as brain of a system while intelligence algorithms form brainpower of its autonomy. Sensors operate to perceive their surroundings and provide information to the processor which then processes the received information and further controls pertinent actuators to drive the system accordingly. Autonomous mobile robots have to continuously interact with environment, while exercising the assigned tasks [2]. Environmental conditions, difficulty of tasks, product features, different variants, configuration, short timescales and cost are the main factors that determine complexity of robotic projects [2]. Robots with more than one processor are also being developed which not only facilitate fast processing but allow simultaneous execution of multiple tasks as well [3].

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Intelligence algorithms are developed to empower such systems with ability of decision making based on the planned intellectual processes. These strategies of decision making, problem solving and undertaking mission objectives form whole intelligence of a sovereign system. Programming is subsequently used to embed such algorithms and logics in processor(s) thus making it "autonomous".

An essential step, before beginning a project is to identify and define project's requirements perfectly. If objectives are not clear, then most probably the materialized product turns up to be different from the one which was required at initial level [4]. Project planning, scheduling of phases and outlining development strategies at early stage not only save substantial amount of time during product development but also keep it in compliance with requirements and objectives.

Specifications of the product are developed in the light of project requirements. Selection of components, configuration and system level architecture through conscientious design and simulation provides substantial synergy in robotic systems [5]. For an optimal product, choice of components must be in compliance with defined system specifications. Ideal systems are self-reliant, adaptable and fault tolerant. They are developed using minimum resources with highest possible efficacy. A simple technique for reducing complexity of project is to divide entire system into subsystems and the subsystems further into their units depending on degree of complexity.

Development should be initiated from production of simplest unit or subsystem towards complicated ones. Each unit or subsystem, after its development, should be accurately tested and its required output parameters must be validated. Proper inspection, testing and step by step verification of unit(s) parameters and subsystem(s) parameters are mandatory for timely identifying faults and smooth progression of project. Late identification of errors or faults results in increased wastage of time and cost for amending or recovering it. System integration is a complicated process in which communication failure and compatibility issues between units or subsystems are major problems faced [6].

Each subsystem is developed step by step and subsequently tested as well as verified. It is not necessary that the subsystems which are functioning well separately will also work fine in integrated form. Generally, compatibility issues

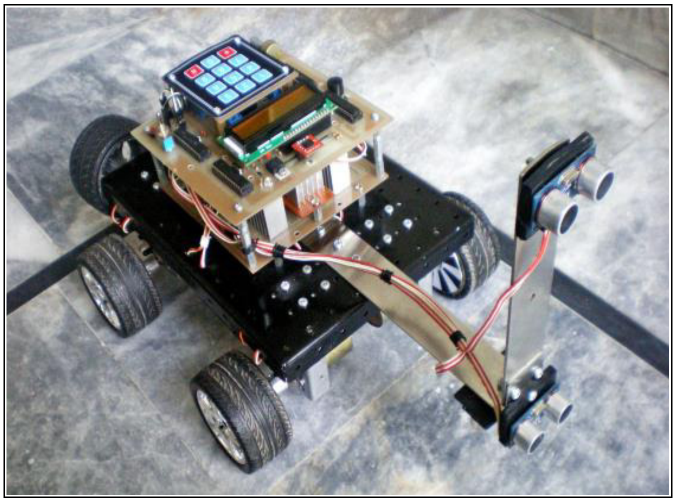


Fig. 1. *The ROBUST*.

arise in integration process due to mismatching of requirements and constraints of the interfaced modules that can be avoided by keeping parameters and constraints of each subsystem strictly in compliance with requirements of others. After development, the system is thoroughly tested, refined to optimal extent at system level and is verified.

The ROBUST has been designed to sense and avoid obstacles, ditches and steep slopes (slopes inclined more than 30°) while performing autonomous navigation from one location to another. However, it is automated to climb and pass through slopes having low inclination i.e. 30° or less (see Fig. 5). Value of destination point is provided by the user. Three ultrasonic sensors have been used for obstacle, ditch and slope sensing while IR sensors with 24-bit optical encoders (having 12 white and 12 black slits for reflecting and absorbing IR rays from IR transmitters to IR receivers, see Fig. 6) have been installed for sensing *revolutions per minute* (rpm) of wheels to govern the speed of robot as well as distance coverage. A magnetometer has been employed for direction sensing purposes. After reaching end point, autonomous robot arrives back at initial location by following the same routine.

The ROBUST has four powered wheels. Its weight is approximately 5 kg while whole assembly fits in dimensions of 50.8 cm x 30.48 cm x 40.64 cm (20-inch long x 12-inch wide x 16-inch high).

II. AUTONOMOUS ROBOT DEVELOPMENT PROCESS

Engineering robots in present age is generally no more a difficult task yet much advancement is desired because of their huge scope and numerous applications. Availability of commercial-off-the-shelf (COTS) components in vast varieties and categories has strongly facilitated system development processes [1]. Readymade modules can be selected as per requirements and interfaced together thus materializing a complete system [7]. Utilization of *COTS* components certainly saves time which was to be spent on their indigenous development however cost of project gets increased. Design and development of a robot must consider the available budget, acceptable time and degree of quality needed which correspondingly all depend on project requirements [8]. Development process of autonomous robots is based on following phases.

- Defining Project Requirements and Objectives
- Project Planning
- Components Selection
- Development of Intelligence Algorithms
- Design & Development of Subsystems
- Structure Fabrication
- Assembly, Integration and Testing
- System Optimization and Tuning

A. *Defining Project Requirements and Objectives:*

The requirements and objectives of project are stated as below.

- A wheeled robot shall be developed that could navigate from one point to another.
- Navigation of robot shall be completely autonomous.
- The extent of navigation shall be within 15 m x 15 m arena.
- Location of destination point will be specified by user.
- Standard speed of robot shall be around 0.5 m/s while high speed shall be 1 m/s at max.
- Robot shall sense and avoid obstacles en route without collision.
- Obstacles taller than 3 cm and broader than 3 cm facing the robot must be detected.
- Robot shall sense and avoid ditches en route without dipping or falling.
- Ditches deeper than 3 cm must be detectable.
- The robot shall be able to measure inclination of slopes en route.
- It must climb and pass through slopes that are inclined not more than 30°.
- Slopes inclined more than 30° shall be avoided without collision.
- After reaching target location, robot shall automatically return to initial location by keeping itself in conformance with the defined constraints.
- The robot shall be designed for smooth surfaces only.
- Structure of robot must be rigid enough to endure up to 15 kg weight.
- Robot must be sufficiently powerful to drive up to 10 kg payload.
- Robot must have 4WD scheme for robust and quick motion.

B. *Project Planning:*

Product specifications were planned on the basis of defined requirements and objectives of project. *The ROBUST* was to take input from user regarding destination point, thus a keypad was to be employed for giving inputs and an LCD for display purposes. Microcontrollers embedded with intelligence algorithms were intended to be used for performing tasks and making the robot autonomous. Navigation algorithms were decided to be developed according to "*Cartesian Coordinates System*" (CCS) in which navigation to a point in 2D plane demands frequent on-board sensing of distance covered by robot as well as its heading.

For direction sensing, a magnetometer was required whereas distance measurement was planned to be odometry based. Idea was to prepare reflective optocouplers (each optocoupler consisted of an IR sensor and an optical encoder) using discrete components (see Fig. 6). Encoders were to be attached on the inner side of all wheels to monitor their rpm values using IR sensors. Output of each optocoupler would allow measuring rpm of the corresponding wheel. As wheel circumference can be physically measured, one revolution of wheel covers distance equal to its circumference. After reaching destination point, *The ROBUST* would pop up sound for 3 seconds and return to initial location by following the same routine of avoiding obstacles, ditches and steep slopes.

For effective load carrying capability and 4WD robust motion, four DC motors having sufficient torque and rpm values were required. Due to minute variations in rpm values of motors (for a fixed voltage) and differences in settling time of their transient responses, robots are generally unable to move in a straight line. There was a need to synchronize values of motor rpms and such rpm matching was planned to be implemented by getting feedback from the optocouplers.

Wheels play significant role in mobility of robots. Diameter, design, width and tractions of wheels are main factors that affect motion of robots. Rough tractions facilitate skid free motion. Wheels with large diameters allow robots to travel more distance per revolution as compared to small wheels however motors with high torque values (for a fixed amount of load) are required. Wide wheels allow robots to carry more weight with less slippage vulnerability because of the increased contact area with floor.

The ROBUST was to navigate on smooth surfaces, thus stair case approach for navigation was selected which requires right angled turn at each step [19]. Differential drive turning mechanism was chosen for achieving fast and sharp turns. In the employed differential drive turning scheme, right sided wheels and left sided wheels are revolved in opposite directions with suitable rpm values to rotate the robot until required heading is achieved. For a right turn, right sided wheels are rotated backward and left sided wheels are rotated forward (vice versa for the left turn). Consequently, the robot gets rotated in the azimuth plane keeping its position unchanged. Extent of *The ROBUST's* rotation was also planned to be controlled by using feedback of the magnetometer.

Obstacle, ditch and slope sensing was intended to be performed by means of three ultrasonic sensors, out of which two sensors were to be clamped at different heights for sensing slopes and obstacles as shown in Fig. 4. Obstacles generally have slopes more than 30° hence all objects with inclination greater than 30° were considered as obstacles and were decided to be avoided during navigation. The third sensor was to be pointing downwards for depth sensing. To avoid falling into ditches, ultrasonic sensors were planned to be mounted on an extended bar which would be kept ahead of robot's anterior surface for detecting ditches well before the edges of wheels reach vicinity of ditches or trenches.

As power source, a rechargeable DC battery of 12 V and 9 Ahr was decided to be used. Selection of battery in terms of its energy capacity was based on calculated system power requirements and the defined backup time. For components with 5 V requirements, *L7805* voltage regulators were planned to be used. Durable robotic structure was desired to grip all components as well as to withstand up to 15 kg weight. Thus, a reasonably strong, rigid and light weight material was to be used for manufacturing robot's chassis and other structural components.

C. Components Selection:

Choice of components was based on the project plan. Except four reflective optocouplers which were self-made using discrete components, following major equipment was procured.

- Four DC motors with 30:1 gearbox, 8-kgcm torque and peak rpm of approximately 350 revolutions.
- Three *PIC-16F876A* microcontrollers.
- Three *HC-SR04* ultrasonic sensors.
- *HMC-6352* magnetometer.
- Rechargeable *Lithium Ion* Battery of 12 V and 9 Ahr.
- Four rubber wheels having 3-inch diameter and 1.5-inch width.
- Sound buzzer
- 2x16 LCD and a 4x4 keypad.
- Three *L7805* voltage regulator ICs and four *L298* H-bridge ICs.
- Aluminum sheet (24-inch x 24-inch, 2 mm thick).

D. Development of Intelligence Algorithms:

Autonomous navigation to a location in 2D plane requires regular on-board cognizance of two parameters i.e. the distance with respect to reference point and robot's heading with respect to reference angle [9]. A navigation scheme was developed with a reference frame based on *CCS* (see Fig. 2). In this reference frame, initial position of robot is considered as origin which is also the reference point for entire navigation. Destination point is fed by user in *centimeters*. Heading of *The ROBUST* in the azimuth plane at starting point is equal to 90° which is also the reference angle for its direction measurement. All angles within active frame of reference are as per *CCS*.

According to navigation algorithm, robot covers primarily the vertical component of displacement vector **D** until no obstacle is faced. After covering this vertical distance, *The ROBUST* changes heading to 0° and covers horizontal distance (see Fig. 3). Once reaching the target point it stays there for 3 seconds, changes heading to 180° and then returns to the initial location by following same routine of covering vertical distance first and horizontal distance afterwards. Figure 3 allows visualization of embedded navigation algorithm with different obstacles in *The ROBUST's* path.

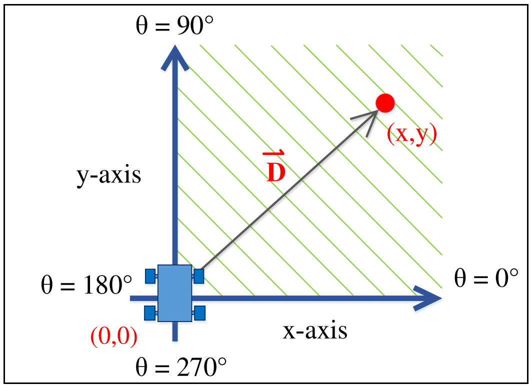


Fig. 2. Reference frame.

If an obstacle, ditch or a steep slope is faced while covering the vertical distance *y1*, robot will save the covered distance in memory, rotate right to change heading towards 0° and will cover horizontal distance *x1* until no obstacle is faced. After covering the horizontal distance, it will turn left by changing direction towards 90° and cover the remaining vertical distance up to the target point. After staying 3 seconds at its destination, robot will shift its heading towards 180° and move to initial location by following the same routine. Identical procedure is followed for at most six hurdles at each path.

$$\vec{D} = (Dx, Dy) \tag{1}$$

$$Dx = \sum_{i=1}^{n} x_i = x_1 + x_2 + x_3 + \dots \dots \dots x_n \tag{2}$$

$$Dy = \sum_{i=1}^{n} y_i = y_1 + y_2 + y_3 + \dots \dots \dots y_n \tag{3}$$

Where n=6. *Dx* and *Dy* represent vertical and horizontal components of displacement vector (**D**), respectively. *Pose* of robot holds information about its position and orientation in a 2D and 3D plane [9], [20]. As discussed in [20], transformation matrix ***X*** for calculating *The ROBUST's* pose is represented in Eq. 4–9.

$$\mathbf{X} = \begin{bmatrix} \mathbf{R} & \mathbf{t} \\ 0 & 1 \end{bmatrix} \tag{4}$$

$$\mathbf{R} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \tag{5}$$

$$\mathbf{t} = \begin{bmatrix} x \\ y \end{bmatrix} \tag{6}$$

$$\mathbf{X} = \begin{bmatrix} \cos\theta & -\sin\theta & x \\ \sin\theta & \cos\theta & y \\ 0 & 0 & 1 \end{bmatrix} \tag{7}$$

In Eq. 5 and Eq. 6, ***R*** is rotation matrix and ***t*** is the translation matrix of *The ROBUST's* pose, respectively. The transformation matrix ***X*** facilitates estimation of robot's positions and heading w.r.t the reference frame. Variations in position and yaw angle of robot can be calculated by using these relations. Programming of *The ROBUST* has been done on basis of the provided equations.

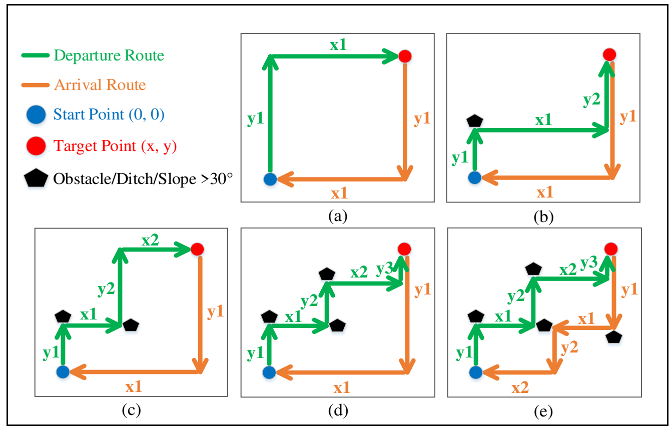


Fig. 3. Few cases of navigation algorithm.

$$\mathbf{P}_{global} = \mathbf{X} * \mathbf{P}_{local} \tag{8}$$

$$\mathbf{P}_{local} = \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{9}$$

Where *x* and *y* are distances covered by the robot in *x* axis and *y* axis with respect to its preceding heading and position as a reference. ***X*** represents the current pose, ***P**_global_* represents absolute position of robot with respect to global frame of reference and ***P**_local_* represents position of *The ROBUST* with respect to its current heading angle.

E. Design & Development of Subsystems:

The ROBUST was divided into three subsystems.

1) Obstacle, Slope and Ditch Sensing Module: In this subsystem, a microcontroller was interfaced with three ultrasonic sensors. Its function was to detect ditches and obstacles as well as to measure slope inclinations. All objects including slopes of inclinations greater than 30° were defined as obstacles. It was developed step by step and initially only *S2* ultrasonic sensor was integrated with microcontroller for obstacle detection. The microcontroller was programmed as per datasheet of sensor and circuit was fine-tuned to get effective results. After preliminary optimization, other two sensors *S1* and *S3* were incorporated in the design with few modifications in code for empowering *The ROBUST* with slope sensing and ditch detection capabilities. Figure 4 highlights the concept of obstacle detection, ditch detection and slope estimation.

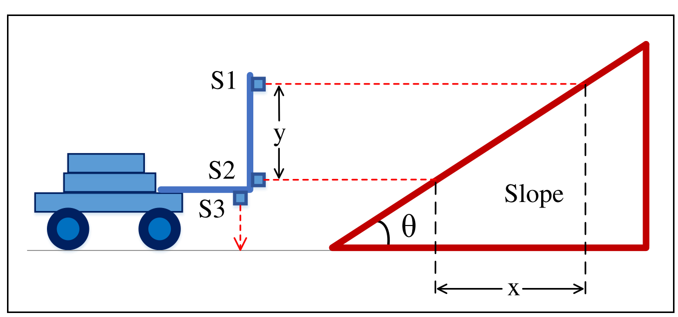


Fig. 4. Obstacle, ditch and slope detection concept.

Slope inclination can be estimated using following relation.

$$\theta = \tan^{-1}\frac{y}{x} \tag{10}$$

Where, y is the difference between heights of *S1* and *S2*, x is difference between measured ranges of *S1* and *S2* while θ is the slope inclination. Value of y was measured physically which is 20.32 cm (8-inch) whereas value of x was calculated on-board using the output of ultrasonic sensors. As slope inclination gets steeper, range difference x gets decreased, hence for right angled slope, the range difference is almost 0 cm. Function of *S1* and *S2* was to detect obstacles and to sense slope inclinations based on joint collaboration. Threshold distance for obstacle and slope avoidance was set to be 25 cm.

Ditch detection was aimed to identify trenches with the help of down pointing sensor *S3*. The *S3* sensor was frequently triggered to sense depths (see Fig. 4). Whenever a ditch deeper than 3 cm appears, the sensor senses increase in depth and master microcontroller takes decision of changing robot's path. Ditch detection threshold value (3 cm) can be varied as necessary. Early detection of ditches is required to break momentum of the approaching robot before its wheels reach vicinity of ditches. Hence, *S3* was mounted on a bar which is extended 17.78 cm (7-inch) ahead of *The ROBUST's* anterior. Similarly to avoid collisions of this extended bar with objects, the sensors *S1* and *S2* were clamped on its verge at heights of 38.1 cm (15-inch) and 17.78 cm (7-inch) from ground, respectively.

Table I shows the practical results of *HC-SR04* ultrasonic sensors. These sensors provide erroneous results for ranges of less than 2 cm. Object range can be computed from *round trip time* (t_R) and speed (C_S) of ultrasound waves by using Eq. 11 with the help of a microcontroller [21]. Propagation of ultrasound waves gets affected by wind as well as by temperature variation [19], [21]. Eq. 12 shows relation between speed of these waves and temperature (T in centigrade) [21].

$$\text{Range} = \frac{C_S \, x \, t_R}{2} \tag{11}$$

$$C_S = 20.05\sqrt{T + 273.16}\ \text{m/s} \tag{12}$$

With the help of several experiments in a spacious room and constant environmental conditions to avoid influence of external factors on results, the measured beam width of *HC-SR04* sensors in azimuth plane at range of 1 meter was found to be approximately 26.91° whilst their beam angles for elevation and depression were found to be 13.46° and 13.79°, respectively.

During slope sensing, the ultrasonic waves triggered from sensors get diverted from *line of sight* path as they strike smooth surfaces of slopes. Consequently, echo received for large ranges (greater than 25 cm) at ultrasonic sensors cannot get sensed completely by the sensors. However for small ranges (less than 25 cm) better results were observed and smooth surfaced inclinations of more than 65° can be estimated as shown in Tab. II. In order to distinguish slopes of inclination more than 30° from ones having inclination of less than or equal to 30°, the slope surfaces were made rough as shown in Fig. 5. In this way waves from sensors *S1* and *S2* do not get deflected completely and a considerable amount of echo is received by them for which they were fine-tuned to fulfill the requirements.

2) Distance Measurement & Speed Control Module: This module consisted of three microcontrollers interfaced in master-slave configuration with the help of I2C protocol. Master microcontroller was controlling two slaves. Each slave was further interfaced with two DC motors via *L298* H-bridge ICs for varying and controlling their rpm values and consequently the robot's speed. Dual H-bridges of each L298 IC were used in parallel combination to increase output current. A simple closed loop control scheme with a unity gain proportional controller was adopted for motors control. Speeds of all motors were simultaneously adjusted by varying duty cycle of 25-khz PWM signals being fed to the H-bridge ICs. *CCP* modules in *PIC* microcontrollers were used for generating PWM signals.

Feedback for rpm values of wheels was provided to slaves by the optocouplers. The optocouplers consisted of IR sensing

TABLE I. RESULTS OF *HC-SR04* ULTRASONIC SENSOR

Actual Range (cm)	Measured Range (cm)
2	2.19
5	5.1
10	10.09
50	50.17
100	100.26
200	200.32
300	300.37
400	400.41
475	475.45

TABLE II. RESULTS OF SMOOTH SURFACED SLOPE ESTIMATION

Actual Slope	Measured Slope
65°	67.14°
70°	71.59°
75°	75.33°
80°	80.67°
85°	85.34°
88°	88.26°
90°	90.08°

Fig. 5. Structure with rough surfaced slope (inclination: 30°).

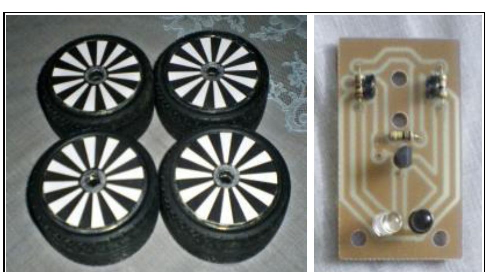
modules and 24-bit incremental encoders attached at the inner side of wheels (see Fig. 6). The encoders used to rotate with wheels allowing IR sensing modules to generate pulses. Consequently, output of whole optocoupler was produced which was fed to the corresponding slave microcontroller for pulse counting purposes and to implement closed loop control scheme for corresponding motors.

Required typical speed of robot was around 0.5 m/s while maximum speed was 1 m/s for which the calculated motor rpm values with wheels of 3-inch diameter came out to be 125.35 revolutions and 250.70 revolutions, respectively. Robot's speed was computed on the basis of arithmetic mean of four rpm values (of four wheels) in order to minimize errors and uncertainties. Table III shows differences between rpm values of the motors against applied voltage. Such rpm variations and the differences in transient responses of motors hinder the open loop control scheme for straight drive of wheeled robots.

Distance measurement was also performed by slaves on the basis of pulse counting. Both slaves used to provide information regarding covered distance to master microcontroller about rotations of the corresponding wheels. The master then used to average these four values and calculate the covered distance. Since wheel circumference is 23.94 cm, the resolution of 24-bit optical encoders was found to be 1.995 cm (as 23.94/12=1.995). Therefore each pulse generated by the optocouplers was considered as *covered distance* of approximately 2 cm by the robot in forward direction.

TABLE III. RPM VALUES OF DC MOTORS W.R.T. APPLIED VOLTAGE

Applied Voltage	RPM Values			
	Motor-1	***Motor-2***	***Motor-3***	***Motor-4***
0	0	0	0	0
1	20.25	21.15	18.07	16.80
2	50.10	50.70	48.38	46.65
3	81.81	82.33	80.98	80.91
4	112.76	113.44	113.14	112.09
5	145.82	145.82	145.07	144.69
6	175.61	175.92	175.47	175.10
7	207.48	207.40	207.93	209.58
8	236.83	236.68	237.78	236.68
9	267.91	267.99	268.14	268.06
10	300.19	299.97	301.54	304.84
11	330.45	332.40	334.80	339.45
12	360.78	357.33	361.15	367.52



(a) (b)

Fig. 6. (a) Optical encoders fitted on wheels. (b) IR sensing module.

$$\text{rpm} = \left(\frac{\text{Frequency of optocoupler}}{\text{Number of black or white slits}}\right) \text{x } 60 \tag{13}$$

$$\text{Speed} = \left(\frac{\text{Average rpm of wheels}}{60}\right) \text{x Wheel circumference} \tag{14}$$

$$\text{Distance} = \frac{(\text{Wheel circumference x Pulse counts})}{12} \tag{15}$$

Microcontrollers cannot directly drive DC motors because the maximum current which can be obtained through each I/O pin is only 25 mA [19]. High torque DC motors typically require large values of current in order to be driven. If single transistor is used as switch for motor drive then motor direction cannot be controlled as the circuit cannot change voltage polarity. H-bridges enable voltages to be applied across loads in either polarity [10]. Therefore they facilitate speed control as well as direction control capabilities for driving motors.

3) Direction Sensing Module: Direction sensing module was developed to compute robot's heading and to control its turning angle. It was based on *HMC-6352* magnetometer interfaced with a microcontroller. The module was tested multiple times and results indicate that *HMC-6352* magnetometer is very sensitive to nearby magnetic fields. It is not a tilt compensated magnetometer and thus provides incorrect results if not kept perfectly horizontal with respect to ground. Non-magnetic attribute of aluminum was proved advantageous for avoiding magnetic interference with the magnetometer and providing shielding effects. The output of *HMC-6352* magnetometer gets distorted by DC batteries, proximate bolts, screws, metallic parts, motors as well as rods and beams present within floors and roofs of buildings.

Regardless of such interferences, the magnetometer provides accurate direction of north. For considerable results it should be mounted about 1-feet higher than other components, should be kept parallel to ground surface and calibrated within the subject environment. However, calibrated compass was found worthwhile only in environments w.r.t which calibration was done. To further improve compass readings, it can be used together with an accelerometer [11]. Table IV shows the results of *HMC-6352* magnetometer (after calibration w.r.t subject environment) measured by keeping north as reference direction at 0°.

TABLE IV. RESULTS OF *HMC-6352* MAGNETOMETER

Actual Angle	Measured
0° or 360°	0°
30°	29°
60°	59°
90°	91°
120°	118°
150°	147°
180°	184°
210°	211°
240°	238°
270°	271°
300°	303°
330°	332°

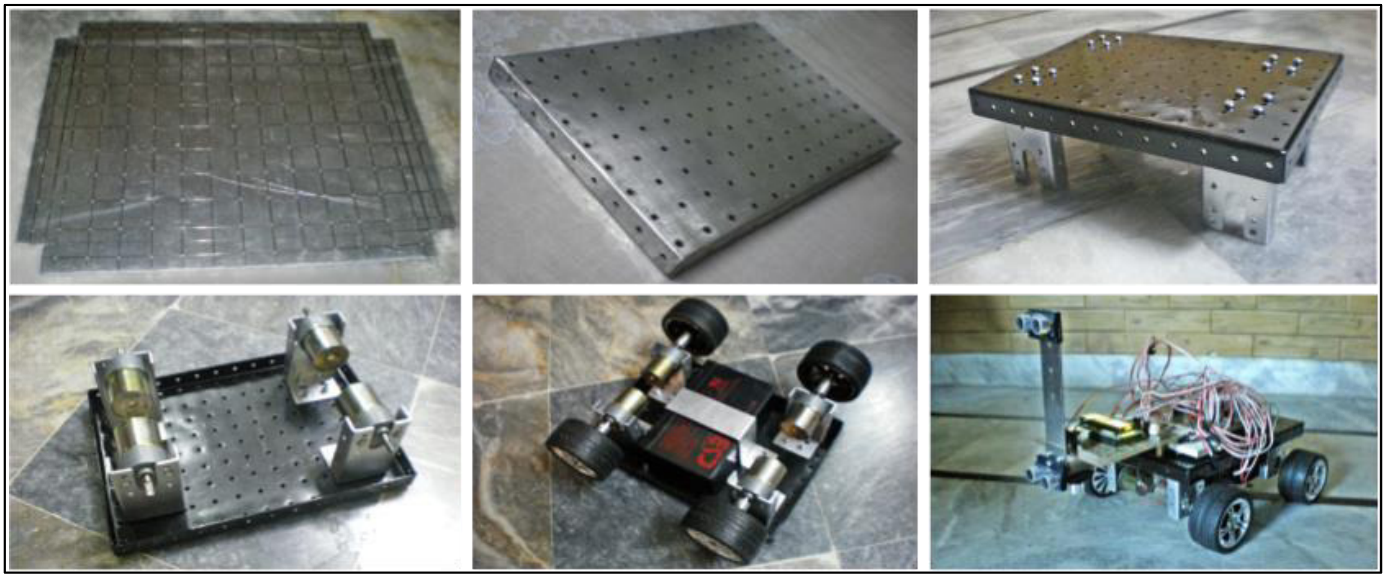


Fig. 7. Assembly of *The ROBUST's* structure.

F. Structure Fabrication:

A robot gives erroneous motion if its structure is defective or inaccurate. Robotic structure with strong magnetic properties can affect magnetometer readings. Therefore, 2 mm thick aluminum sheet was selected for fabricating structure of *The ROBUST* as it is light weight, non-magnetic and rigid enough to bear heavy loads. Figure 7 shows step by step assembly of complete structure.

A chassis of 11-inch x 8-inch (after bending 0.75-inch at right angle from all edges) comprising a grid of *through holes* (4 mm diameter) for mounting components was prepared with precise dimensions and accurate bend angles. To fix motors with chassis, aluminum brackets were prepared by initially cutting aluminum sheet, drilling holes and subsequently bending it. These brackets were designed in a way that motors could be fixed at adjustable distances from the chassis. In this way the chassis can be raised from ground level at variable heights as required. Vertical length and width of each bracket was 4.5-inch and 3-inch, respectively. Each bracket was also 0.75-inch bent at 90° from both vertical edges to gain additional strength.

DC motors typically have "**D**" shaped shaft. Coupling of wheels with motors is a complicated task. It can be done by fabricating a structure that can bridge both components. Hence, for fixing shaft of each motor into the opening of corresponding wheel, a cylindrical structure was prepared which used to grip the motor shaft from one side as well as got attached within wheel opening at the other side. A bar of stainless steel bent at 90° as seen in Fig. 1 and Fig. 7, was fabricated for clamping three ultrasonic sensors. Among which, two sensors were mounted at different heights for slope estimation.

Battery is the heaviest component so it was fitted with a bent aluminum bracket at central position under the robot's chassis. 5 mm thick rubber strips were placed between chassis and the battery to grasp it tight and to avoid unwanted sounds which arise due to loose clamping during drive.

G. Assembly, Integration and Testing:

After development of structure and validation of allocated tasks of the subsystems, assembly and integration were carried out. All subsystems were merged together to form a complete robotic system having the required features. Components were assembled on robot's chassis with symmetry to keep its weight balanced. In this way, total weight of the robot gets divided equally on every wheel. Master microcontroller was connected to three ultrasonic sensors and a magnetometer for sensing obstacles, ditches, slopes and heading of *The ROBUST*. Both slave microcontrollers were connected with four motors and four optocouplers to control robot's speed as well as to compute its distance coverage. Slaves are responsible to communicate all information to the master.

A major problem faced after integration process was interference of ultrasonic sensors with each other. Appropriate separation between *S1* and *S2* sensors was done to avoid echo of one sensor getting detected by others on the basis of testing. Besides this, operation of each sensor was divided into a different time slot on the basis of round trip time of ultrasonic waves at maximum range. The minimum width of each of these time slots was set around 27 ms with safety margin (see Fig. 8).

Another issue encountered was the power constraint of *L7805* voltage regulator IC which can provide maximum output power up to 7.5 W. For individual subsystems, single voltage regulator was enough but after integration, the combined power requirement of subsystems increased. Hence a sole voltage regulator was insufficient to meet power requirements for entire system. Separate voltage regulators were employed with every subsystem as a solution which would also allow installation of additional components with respect to future perspective.

To solve integration problems, subsystems were made compatible with each other and interfaces of each subsystem were tested and validated before and after integration process. Integrated system assembly was tested step by step each time a subsequent subsystem was linked with the preceding one. After assembly and integration, testing at system level was done to verify that system is fulfilling its requirements.

H. System Optimization and Tuning:

In this phase, robot was optimized and tuned at hardware and software level for optimal operation. Optimization of the sensing rate of ultrasonic sensors, magnetometer and optocouplers was performed. Complete code of *The ROBUST* was improved and fine-tuned accordingly. Update rate for magnetometer and ultrasonic sensors was set at 10-hz and each sensor was giving single reading in every time interval of 100 ms. Figure 8 shows the timing diagram of operation of magnetometer and three ultrasonic sensors.

Stop time *(time required to change state of motion to the state of rest)* of robot was improved by testing it multiple times in standard speed as well as high speed. For sudden breaks, thin pulses of reverse polarity were applied to motors. The extended length of front bar for ditch detection was adjusted on the basis of robot's *break time* which was optimized around 234 ms. With a speed of 0.5 m/s, *The ROBUST* would cover less than 11.7 cm during deceleration in 234 ms. Hence the finalized length of this bar was kept 17.78 cm (7-inch) long including safety margin. To avoid collision of front bar with slopes during climbing, its level from ground was kept around 15 cm high. For a 30° inclined slope (worst condition) which the robot has to climb at most 25.98 cm distance from the edges of wheels to the front bar's tip is possible to avoid collisions with slope's surface. Therefore, this length was set around 17.14 cm which is reasonably safe.

Error in distance measurement due to slippage of wheels was another issue. On slippery surfaces wheels keep on slipping but robots are unable to cover the corresponding distance, physically [19]. Sensors perceive this situation as covering of distance due to pulse generation. Consequently, result is accumulation of error in terms of distance and speed measurements. The accumulated error was minimized at software level by repeated testing and analysis of the data.

When an obstacle having height lower than *line of sight* of *S1* sensor was faced, *The ROBUST* used to perceive this condition as facing of a very low inclined slope [19]. It was due to large difference in readings of *S1* and *S2* as the obstacle gets detected by *S2* while reading of *S1* was much greater than *S2*. To avoid this issue, maximum limit for *S1* sensor was set to be 300 cm. Hence, whenever *S1* sensor showed maximum range and *S2* sensor showed range within 25 cm, *The ROBUST* was programmed to consider the situation as facing of an obstacle instead of slope having low inclination. In order to detect such low height obstacles, pointing direction of *S1* can be tilted downwards or a movable platform can be used for all of these sensors which could change their pointing directions for assisting robot in decision making process as required.

Overall power requirement of the system was calculated to be 55.69 W for worst conditions. The energy capacity of battery is 86.4 Whr at 80% *Depth of Discharge*. Therefore, for worst conditions, the battery can drive *The ROBUST* for 93.08 minutes (1.55 hours) [19].

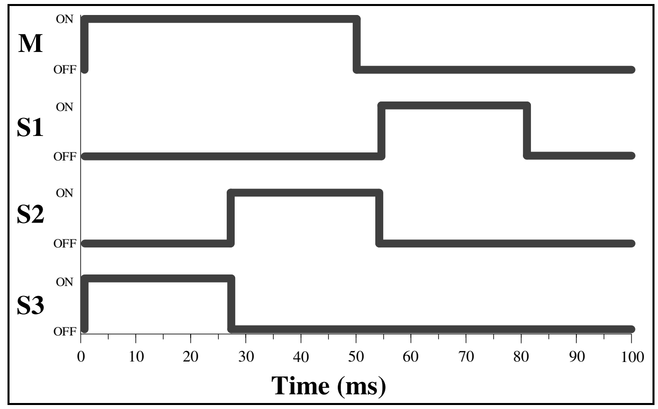


Fig. 8. ON time of magnetometer (M) and ultrasonic sensors (S1, S2, S3).

III. APPLICATIONS, STATE-OF-THE-ART TECHNOLOGY AND FUTURE PERSPECTIVE

Robotics has a vast scope with respect to present and future perspectives. It is typically used when tasks are dangerous, tedious, exhausting and dirty [5]. Depending upon the payloads installed, it can play a profound role in military combats, explosives or land mines detection [19], fire extinguishing [12], 2D/3D mapping, and surveillance of hazardous areas. Military equipment and explosive detectors or mine detectors can be integrated with rovers to materialize required military products. Tasers (electroshock weapons) can empower quick robots to apprehend suspects by making them unconscious with electric shocks and such robots are very advantageous for law enforcement agencies. Rovers integrated with fire extinguishers and fire extinguishing balls can be developed for autonomous and quick firefighting in emergency situations. 2D or 3D cameras can be used in robots for mapping of hostile areas, observation of critical sites and for search and rescue operations.

Lawn mowers, hedge cutters, crop harvesters, vacuum cleaners, seed planters and road sweepers are further application specific robots. Presently, robots are also being used in indoor games and sports including table tennis [13], soccer [14], baseball and basketball [15]. Addition of an appropriate robotic arm can enable robots to lift, sort, cut, paint, weld, and bend materials with respect to industrial requirements. Volcano survey, underwater research and space or interplanetary explorations [16] are some advanced applications of robotics. Ultrasonic sensors cannot work in space environment as no medium is present there for sound waves to propagate through however *LASER* sensors can be used for space applications [19]. Research on autonomous vehicles is also in progress and that time is not far when vehicles will be totally autonomous in which drivers would only provide coordinates of destination points in order to reach there.

State-of-the-art autonomous mobile robots are healthier than *The ROBUST* in terms of accuracy, power consumption, backup time, range of operation, artificial intelligence and processing speed. Precise localization and navigation is being done by the combination of *GPS*, *accelerometer*, *magnetometer* and *motion capture techniques*. Dynamic structures having *omni wheels* or *mecanum wheels* provide the robots more versatility in movement. R&D organizations are developing robots on the basis of concepts grasped by observing and analyzing human body, living animals and the insect counterparts [5]. Numerous application specific robots can be designed on the basis of human senses such as smell, touch, taste, sight, hearing, sustaining balance and learning from environment. A sensor is required for recognizing each particular sense which can thus empower robots with that sensibility and awareness.

IV. Discussion

Drawback of using ultrasonic sensors for obstacle detection in congested areas is the direct relation of their beam widths with range. As range gets larger, their beam widths get wider and the expanse of object detection is increased [21]. Consequently distant objects that are not in the path of robots can get detected and their actual positions are misinterpreted. Therefore such sensors are not suitable for projects in which long range obstacle detection (more than 150 cm) is required in congested places. Ultrasound waves can pass through cloths thus usually thin cloths are not detected by them. Wall edges and inclined surfaces also produce range ambiguities for robots as ultrasonic waves get deflected from the sensor-object *line of sight* (see Fig. 9). Ultrasonic sensors can scan more area per iteration as compared to narrow beam sensors and hence they are suitable for projects which require scanning of large sections.

Profound research is required for accurate remote sensing of slopes that appear in the pathway of autonomous robots. An idea to sense angular or inclined surfaces accurately is by radiating a circular pattern of light waves on them and subsequently detecting pattern's shape by estimating its eccentricity using image processing techniques. When a tilted surface is faced, the circular pattern will change into elongated elliptical form depending on the degree of tilt. Use of *FPGA* instead of microcontrollers is recommended for complex processing tasks as it supports fast and parallel processing, dynamic design, enhanced program memory as well as extra alternatives and design flexibility [17]. Moreover, improved indoor and outdoor navigations can be performed using motion capture technique and *GPS* receivers, respectively.

Addition of wheel suspension system allows rovers to maintain good grip on rough surfaces [19]. No mechanical breaks were included in *The ROBUST's* design due to use of *high torque* DC motors. However the robot slips on slopes under loaded condition. To avoid slippage, mechanical breaks should be installed for better outcomes. At low rpm values the differential drive turning mechanism fails to rotate *The ROBUST*. Acceptable rpm and sufficient torque are always required for generating necessary couple force in wheels to rotate robots. Ordinary wheels can be replaced by omni wheels or mecanum wheels for lateral drive of robot on smooth surfaces without changing its yaw angle [22]. Such wheels make robots highly maneuverable, which could be very helpful in different indoor and outdoor applications [18]. *The ROBUST* lacks sensibility to detect reverse motion and it is unable to distinguish between forward and reverse movement. To make the design more practical, reverse motion detection mechanism should be installed.

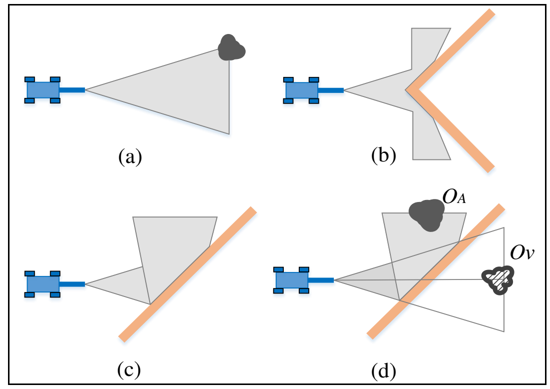


Fig. 9. Ambiguities produced by ultrasonic sensors: (a) Needless detection of a sideway object. (b) Undetected edge. (c) Undetected plane. (d) False perception due to diversion of ultrasonic waves (O_A actual object disregarded, O_V virtual object perceived).

For low frequency PWM signals, vibrations were observed in the motion of robot while high frequencies resulted in heating of circuitry. Motors should be operated at optimum PWM frequency of employed H-bridges. For *L298 IC,* optimal PWM frequency is 25-khz. Using capacitors of recommended values with the electronics is highly important. Final PCB of whole circuit must be developed after verification of the design with *test points* and *battery charging points* at appropriate locations. Wide tracks (more than 1 mm) should be designed for current values greater than 1 A [19], as thin tracks of the board will burn if high value current passes through them [19].

Thickness of black and white slits in optical encoders must be kept larger than incident beam width of IR transmitters (see Fig. 6). If beam width of an IR transmitter is greater than the width of encoder's slits, reflected waves will trigger the IR receiver several times and multiple counts would be generated against a single increment, leading to miscalculation of speed and distance. The resolution of optical encoders will get affected by using too wide slits resulting in accumulation of larger errors. Therefore, narrow beam IR transmitters with encoders having suitable slits are recommended. Replacement of DC motors with stepper motors will allow removal of optocouplers from *The ROBUST* as steppers facilitate accurate position control due to their capability of step based rotation.

Conclusion

In this article, a systematic development process of an autonomous mobile robot named ***"The ROBUST"*** has been described from defining project requirements and objectives to testing, optimization, verification and validation of the end product. The manuscript highlights critical issues, design constraints and experimental results experienced during development of *The ROBUST*. It also describes future perspective of the robot as well as detailed applications related to field. Robotic platform, design and the defined algorithms can be improved and tailored with installation of applicable payloads to develop numerous application specific robots. Major issues of this project include; interference between the three ultrasonic sensors, ambiguities caused by deflection of ultrasound waves from sensor-object *line of sight* due to inclined or angular surfaces, deviations in output of *HMC-6352* magnetometer due to neighboring *EM* fields and accumulation of error in odometry based distance measurement due to slippage of wheels.

The ROBUST has been tested rigorously and it can effectively navigate to target points while detecting and avoiding obstacles and ditches. Estimation of rough surfaced slopes as well as smooth surfaced slopes (those inclined more than 65° only) is productive. Decision making capability of robot about climbing or avoiding rough surfaced slopes which are tuned with ultrasonic sensors is excellent. All requirements and objectives of the project have been successfully accomplished and the overall performance of *The ROBUST* is quick, smooth and vigorous.

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