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ORIGINAL ARTICLE

Development of a vacuum cleaner robot

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Abstract Modern households are becoming more automated thereby delivering convenience and reducing time spent on house chores. While vacuum cleaners have made home cleaning easier, they are largely noisy and bulky for everyday use. It is therefore *sine qua non* to improve the technology of vacuum cleaning to reduce these deficiencies. Here, we report the development of a compact and efficient vacuum cleaner robot for potential office and home use. The developed robot is disk-shaped, equipped with vacuuming and cleaning technology and controlled by Arduino mega microcontroller. It sucks dirt via a retractable dustbin on top of which a cooling fan is mounted, and two sweepers each driven by a 3 V DC motor. The robot navigates via two motor shield controlled rear wheels and a front caster wheel which also governs its turning. Four ultrasonic sensors, placed at 90° apart, detect obstacles and subsequently help the robot navigate. The robot is powered by 3 batteries (28.8 V DC), rechargeable via an embedded AC-DC adapter. It is 12 cm wide and 9 cm tall making it easy for maneuvering its environment. Because of the light weight battery, cardboard based dustbin and small blower used, its weight is about 1.5 kg. The total current consumed is ~1102 mA. When fully charged, a 2200 mAh-capacity battery works continuously for two hours and cleans floor efficiently. With this capability, the device will be deployed for office and home use thereby making cleaning a fully autonomous duty.

1. Introduction

A very notable household chore is floor cleaning which is often considered as unpleasant, difficult, awkward and boring [1]. In most cases, cleaners are hired to do the task rather than the household residents do it. The discomfort posed by this recurrent chore necessitated development of a vacuum cleaner that could assist human with such a task [2]. A vacuum cleaner is an electromechanical appliance commonly used for cleaning floors, furniture, rugs and carpets by suction [3]. An electric motor inside the appliance turns a fan which creates a partial vacuum and causes outside air to rush into the evacuated space [4]. This forces any dirt or dust near the nozzle into a bag inside the machine or attached to the outside.

Current vacuum cleaners, although efficient, are rather bulky and therefore require large manpower for proper functioning. The earlier known cleaners are those of Daniel Hess of Iowa (in 1860) and Ives W. McGaffey of Chicago (in 1868) [5–7]. While the former used bellows to generate suction and gathered dust with a rotating brush, the latter worked with a belt driven by hand-cranked fan making it awkward to operate. In the late 1990s and early 2000s, more efficient sweepers equipped with limited suction power were developed. Some prominent brands are iRoomba, Neato and bObsweep [8].

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Depending on the design target, robotic vacuum cleaners are appropriate for offices, hotels, hospitals and homes [9–17]. However, most cheap cleaners need a better cleaning pattern algorithm for efficient functioning while the smart ones are rather costly, and thus beyond the reach of most homes. These challenges were carefully considered while designing the robot vacuum cleaner described in this paper.

The current robot vacuum cleaner was fabricated from computer scraps, ultrasonic sensors and an Arduino mega2560 microcontroller making it relatively cheap. It navigates rooms using a patterned algorithm and its cleaning mechanism is enhanced by two rotating sweeper placed side by side. Its disk shape has been carefully considered in the design of the sweepers while its effectiveness was evaluated.

2. Consideration and design of the robot's components

The vacuum cleaner contains the wheel, cleaning, electrical and control systems, all working harmoniously to achieve efficient cleaning. While designing these systems; aesthetic outlook, overall weight and electrical connectivity were given appropriate attentions. The general layout (Fig. 1) shows the location of the sweeper motor, axial wheels and servo controlled motor among others.

2.1. The wheel system

We considered the approximate weight of the robot in order to correctly distribute the load on the wheels system. In practice, a good design concentrates the load more on the axial wheel and little on the front wheel [18] because the latter is designed for navigation. The robot conceptual design was such that its wheel system was not symmetrical (Fig. 2a) which implies that wheels were not equally distributed on the structure. Two axial wheels, which are DC-motor driven, permit motion in only parallel directions and generate the torque needed to move the cleaner. The single front wheel, which is servo controlled, steers the robot by actively and promptly switching direction of the wheel. It was designed to facilitate reverse and forward movement of the robot.

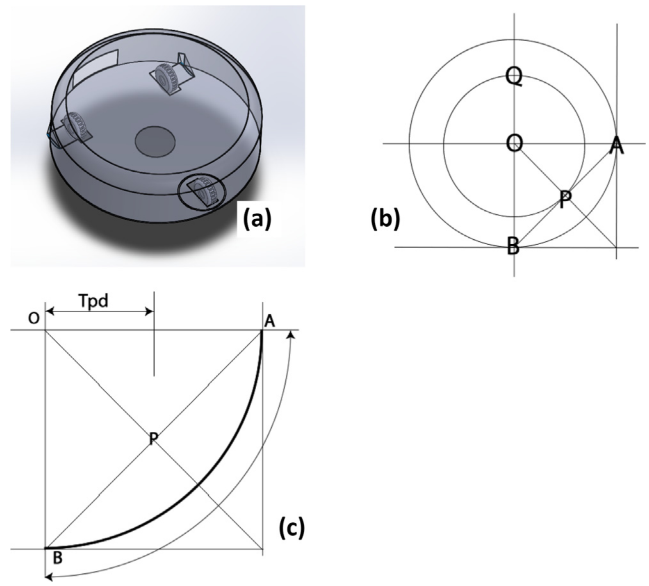

Fig. 2 (a) 3D image of the wheel system, (b) & (c) layout of the wheel system.

The wheel system was carefully and systematically laid out to ensure low center of gravity and accurate motion of the cleaner. The wheels were placed carefully according to the shape of the robot (Fig. 2b). For three-wheel robot, triangulation method was employed to position the wheels (Fig. 2c). Given a robot of diameter D, the sector OAB is given as:

$$\text{Sector OAB} = \frac{90}{360} \times \pi \times \frac{D^2}{4}$$

From Fig. 2(c), $D = 4 \times Tpd$:

$$\text{sector OAB} = \frac{90}{360} \times \pi \times 16\frac{Tpd^2}{4}$$

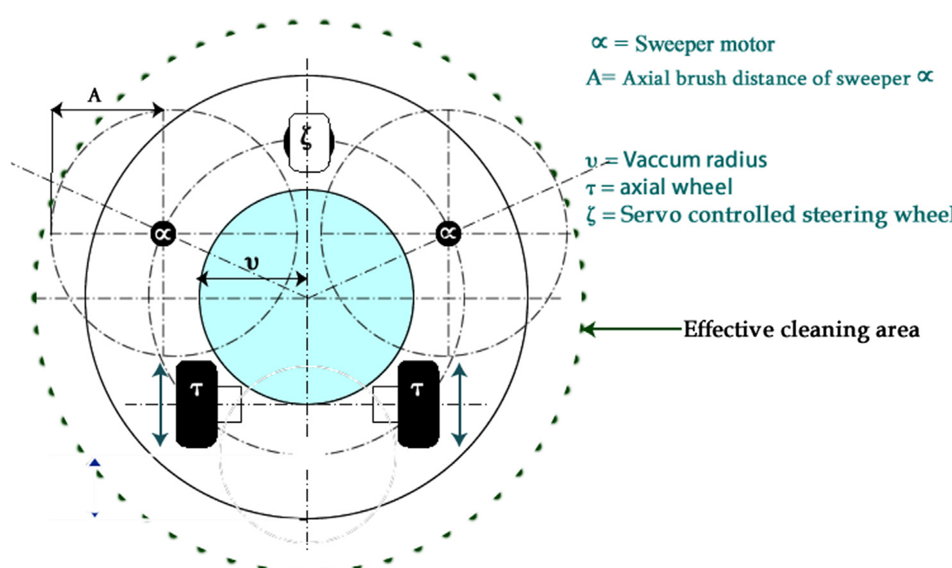

Fig. 1 General layout of the vacuum cleaner robot.

Tdp is the distance of the tyre position axis from the center of the robot and pivot P (the position of the wheel) is Tpd along both horizontal and vertical directions from the centre of the robot. This procedure was followed to locate the position of the second wheel. However, the position of the front wheel was determined by drawing a common circle through the point P using O as the centre, the line BO was then extended to meet the circle at point Q which became the axis of the front wheel (Fig. 2a).

2.2. The cleaning system

The robot is equipped with two rotating sweeper motors, each equipped with two brushes which spin the dirt into the vacuum radius. One of the challenges of a disc shape design is that the brushes tend to overlap and eventually tangle. In the current design however, the sweeper motor was placed halfway between the wheels, thereby prevents the brushes from overlapping (Fig. 1). A careful consideration of the sweeper system layout shows that the robot actually sweeps an area larger than itself as indicated by the effective cleaning area.

2.3. The electrical system and battery

The electrical system is designed to be compact, and most components are mounted on the suction motor. This isolates the system from the body and thus prevents damage due to vibration in case the robot impacts a solid surface. In addition, the compact electrical system helps to balance the load in order to prevent wobbling. A rechargeable lithium-ion polymer battery is used because of its light weigh, high electrochemical potential and good energy density (which is twice that of the standard nickel-cadmium) [19]. The complete layout of the electrical connection is shown in Fig. 3. The relays, ultrasonic sensors, suction motor, the sweepers, among others, are connected to the Arduino mega controller via their respective pins. The LM7805 voltage regulator IC provides 5 V regulated power supply from an input voltage range of 7–35 V and current rating of 1 A. Relay1, Relay2 and Relay3 serve as change-over between external source of energy and Arduino, suction motor and motor shield battery. When POLE 1, POLE 2 and POLE 3 make contact with NO 1, NO 2 and NO 3, respectively, it indicates that external power supply is in use, and all batteries are charging. However, when POLE 1, POLE 2 and POLE 3 make contact with NC 1, NC 2 and NC 3, respectively, it denotes that batteries are in used.

2.4. The control system: sensors and microcontroller

Sensors help robots perceive external environment, make decision and act accordingly. The developed robot uses four ultrasonic sensors (HC-SRO4 model) which are inbuilt with sonar designed to determine distance to an object [20]. This type of sensor offers excellent non-contact range detection (2–400 cm) with high accuracy. Its operation is not affected by sunlight or black material, although acoustically soft materials like cloth can be difficult to detect. It comes with ultrasonic transmitter and receiver module.

Microcontrollers, in general, contain processor cores, memory, and programmable input/ output peripherals. They are used in automatically controlled products and devices, such as automobile engine control systems, remote controls, office machines, appliance and other embedded systems. In this work, we used Arduino microcontroller because it uses single

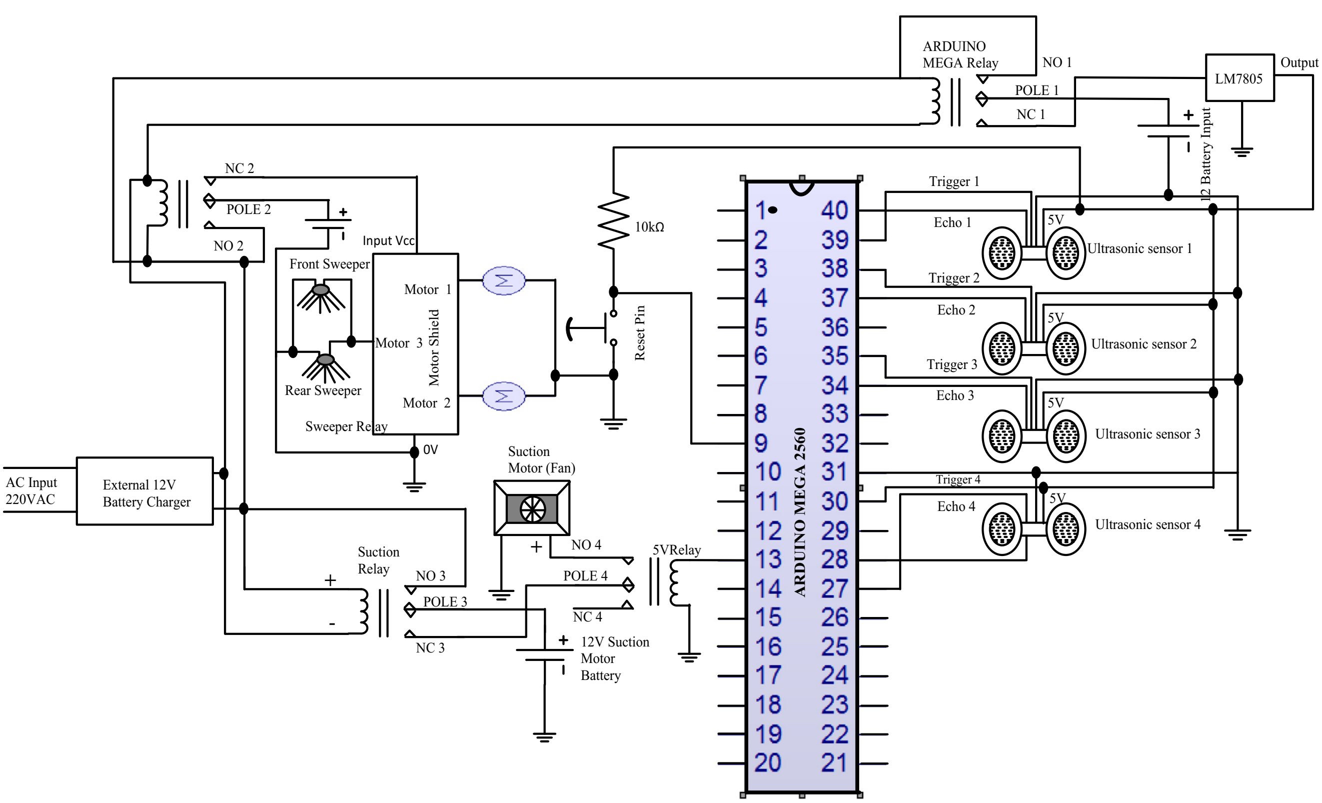

Fig. 3 The layout of the electrical system showing connection between components and Arduino ATmega2560.

board computer, making it popular in professional market. The Arduino is open-source with relatively cheap hardware. While Arduino microcontroller comes in different features depending on the complexity of use, Arduino mega is used for this work because it allows us to use more pins and more memory to retain codes. The Arduino Mega is a microcontroller board based on the ATmega2560. It has 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header and a reset button.

Microcontroller can be powered by simply connecting it to a computer with a USB cable, AC-to-DC adapter or battery. The Arduino microcontroller has IDE in which written program codes are stored (see our code in Appendix). This allows interaction with other software or a hardware device. The microcontroller is connected to the computer via drivers which are often installed automatically.

2.5. Robot navigation

While most vacuum cleaner robot navigation systems are implemented randomly to avoid common obstacles, the navigation system in our device is systematically plotted into a simple routine to by-pass obstacle even in a home with ever changing obstacles like a store. The robot does not memorize this routine only, but rather updates itself on the surrounding and decides according to the routine. The protocol is built for speed and efficiency. This is clearly expressed in the robot's decision when it is placed at the centre of the room, in which case, all the cleaning process is halted until the robot could navigate itself to the starting position.

Fig. 4 is the flow chart for navigation of the developed robot. Once the robot is turned on, it checks its environment and decides the best direction to move. This is done by checking the distance between the left or right sensor to the nearest obstacle, and the side with higher distance is allotted the destination. After this, the robot then checks if it is placed somewhere near the corner of the room. With the back sensor, the distance to the obstacle/corner is estimated. The robot then moves backward until the distance is lower than the safe distance, safeD, which is chosen to be 15 cm. The motor driver on the Arduino motor shield has the ability to apply an engine brake. The brake works by shorting both terminals of the motor together, and it is controlled by Pin 16 (Channel A) and Pin 15 (Channel B) (Fig. 3).

After these pre-operational procedures are completed, the sweeper, blower and the wheels motors are switched on. Then, the robot moves along a straight line until it senses an obstacle as indicated by the safe distance. Thereafter, the robot switches its sensor to the navigating side which keeps changing after every turn since the side facing the destination shifts alternatively from left to right or vice versa. When the distance at the destination eventually approaches the safe distance, it indicates that the robot has reached the other corner of the room or got stuck. In either case, all motors are switched off to conserve power. However, it re-initializes every 15 s to see if the obstacle has been removed or the environment has changed.

3. Results and discussion

The overview of the developed robot and performance evaluation are discussed in this section.

3.1. An overview of the complete robot

The design of the robot required considerations for compactness, efficiency and intelligence. The choice of the disc shape geometry (Fig. 5a) puts it at the forefront of the available conceptual designs. With the disc shape; we were able to limit the number of motorized wheels to two traction back wheels and one servo front wheel (Fig. 5b). Also the sweepers were analytically placed at the most optimum position which increases the cleaning area of the robot without increasing its overall size (Fig. 5b). The dustbin is developed to simultaneously serve as a dirt repository and a cyclone device when fully integrated with the cooling fan (Fig. 5b and d). This indicates that the dustbin is in fact a container inside which a partial vacuum is set up, sucks and retains the dirt without the possibility of spilling the dirt. It should be emphasized that the dustbin is in constant contact with the floor from which dirt is sucked.

In the electrical design consideration, each of the pair of lithium-ion polymer batteries used caters for the Arduino and the motor shield independently because their rates of power consumption differ. While motor shield drives all the motors onboard the robot, the Arduino board serves as the brain which receives impulse from the ultrasonic sensors and controls the motor shield. Also an additional 12 V battery powers the suctioning fan making the overall battery driving the robot to be 28.8 V.

The chassis frame is made from hard board paper because of its flexibility and availability. The Arduino microcontroller board is mounted on the chassis and placed in the front wheel to allow easy access by other interacting components (Figs. 3 and 5c). The four ultrasonic sensors are placed 90° apart while the blower creates vacuum which sucks the dirt (Fig. 5c and d). The two sweepers rotate clockwise and anticlockwise to gather dirt to the vacuuming area. After all the components are assembled on the frame and the programming code was uploaded, the robot was then tested and found to suck dirt effectively, and avoids obstacles efficiently.

The robot is 12 cm wide and 9 cm tall making it easy for maneuvering. It weighs about 1.5 kg only which is due to the light weight battery, cardboard based dustbin and small blower. Other physical dimensions of the major components of the vacuum cleaner are summarized in Table 1. The maximum volume of the dustbin is 0.14 L, which is quite small compared to other advanced vacuum cleaners. This limitation is imposed due to the small diameter of the blower fan. If needed the cleaner can be appropriately scaled up.

3.2. Performance evaluating of the robot

The performance of the developed robot was evaluated based on navigation efficiency, sweeping capability/efficiency and power consumption within the laboratory and office environments. The cleaning performance was tested on a smooth floor on which dry waste such as mixture of rice, fried cassava grains, flours (common household food items) and sand were spread (Fig. 6a). The robot sucked them after two passages from one end of the room to the opposite wall or when an obstacle was encountered. The floor was efficiently cleaned within a minute for floors without obstacles (Fig. 6b). For those with obstacles, it took longer time because the robot had to navigate them. More tests were carried out in offices

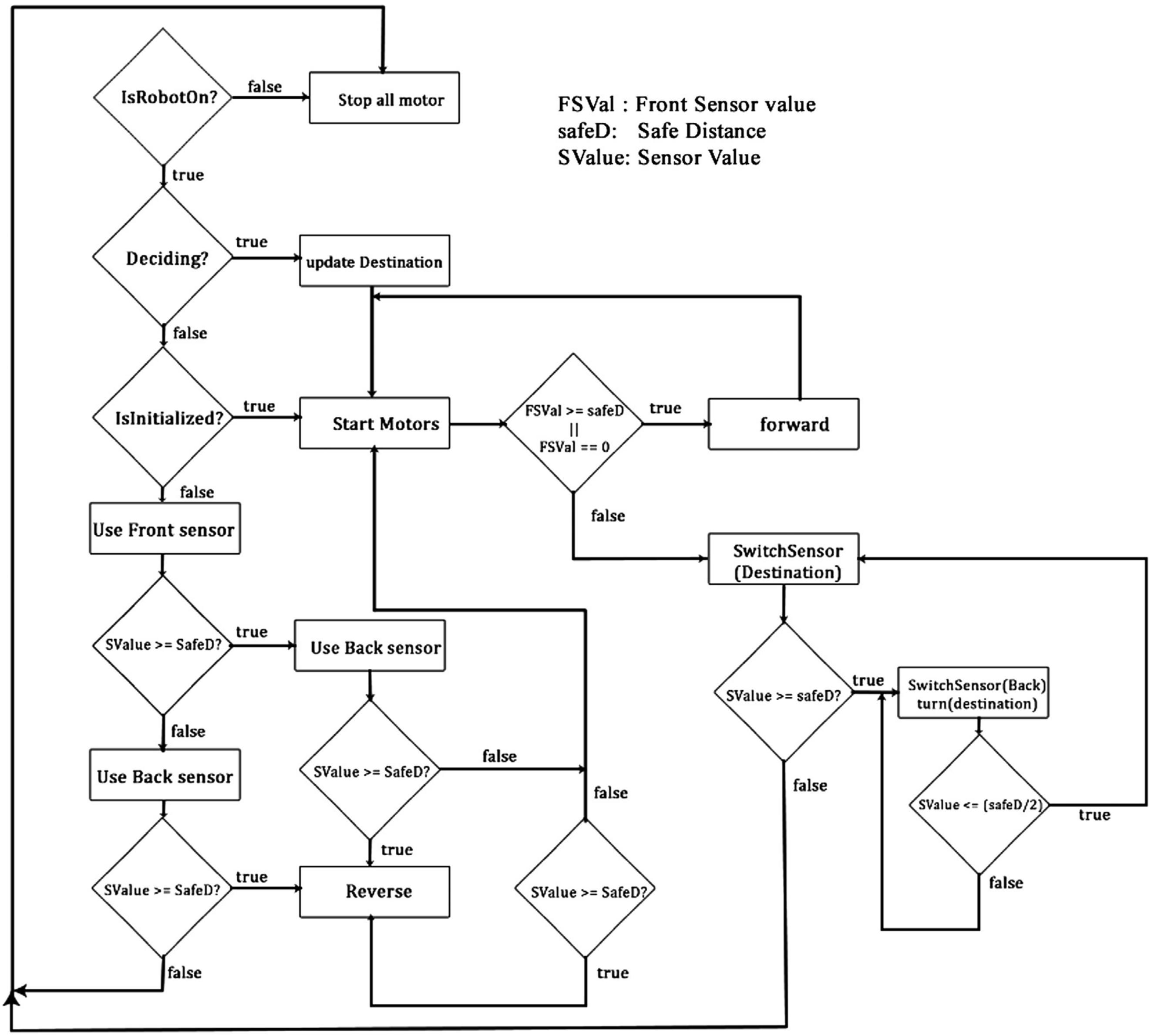

Fig. 4 Flow chart for the vacuum cleaner robot navigation system.

and laboratory spaces, and similar results were obtained. While the robot navigated these areas effectively, occasional glitch due to tiny obstacle was observed. It should be noted that the robot was built to stay very close to the ground to enable more suction and detect small obstacle. Any obstacle that could not be detected must be higher than 1.5 cm which is essentially not a threat to the robot navigation.

The dustbin also worked effectively because the dirt sucked was retained without being spilled off. The dustbin is very accessible making emptying dirt and repositioning the dustbin easy. As regards the power consumption, Table 2 shows the breakdown of the components in the robot along with the maximum current drawn. The total current consumed is ~1102 mA. For a 2200 mAh capacity battery, it was calculated that the cleaner could clean effectively for 2 h before recharging. This is possible since most power hungry components (sweepers, suction motor) are turned off when the robot is just initializing, got stuck or idle. With this capability, the device will be deployed for office and home use thereby making cleaning a fully autonomous duty.

3.3. Challenges and recommendations

The cleaning capacity is limited by the volume of the dustbin. This can be scaled up proportionately. Also, a bigger impeller with more clearance space between the blade and the casing is advisable as this affects the positioning and retrieval of the dustbin. The Motor shield is driven by two L293D IC; these components may become increasingly heated in operation, thus incorporation of heat-sink or more conventional cooling system will be beneficial. There is a need for a more sensors for a large scale domestic capability, for instance, a cliff sensor in case of stairs. Finally, a docking station where the robot can recharge itself once its battery is drained needed to be incorporated for complete automation.

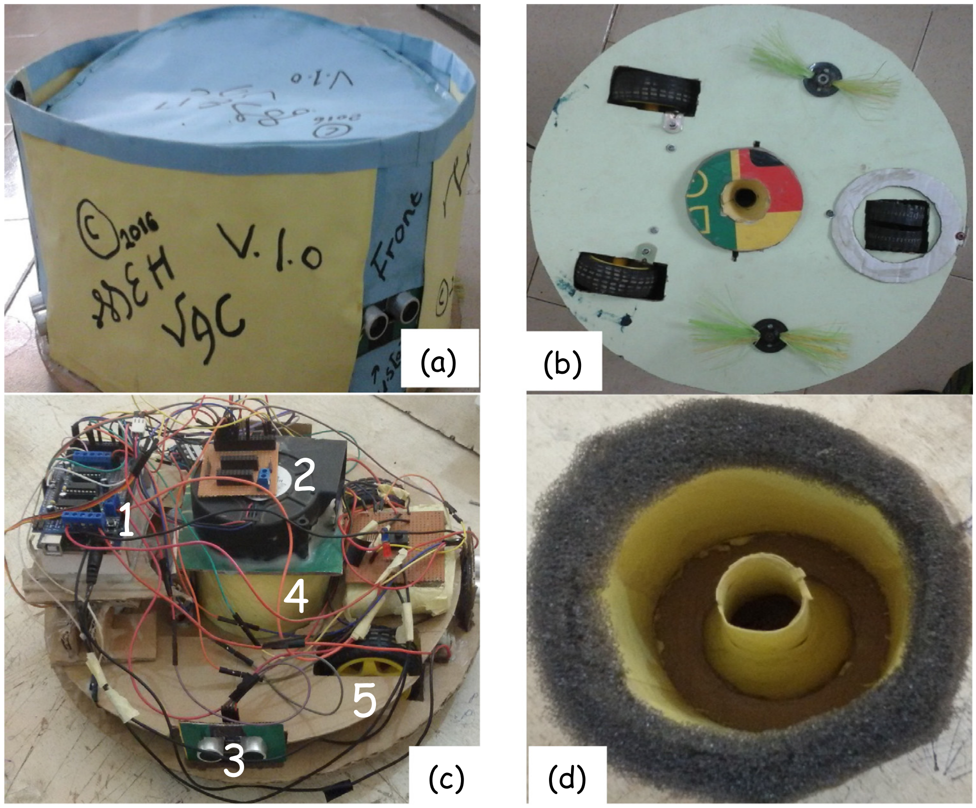

Fig. 5 (a) The developed prototype vacuum cleaner robot (b) Bottom view showing wheels, sweepers and dustbin (c) internal components of the cleaner (d) dustbin. Note: 1-Arduino microcontroller, 2-suction fan, 3-ultrasonic sensor, 4-dustbin, 5-cradboard frame.

Table 1 Physical dimension of major components of the robot.

Characteristics	Value
Overall height of dustbin	8 cm
Outside diameter	9 cm
Triangular height	3 cm
Vacuum diameter	4 cm
Vacuum height	7 cm
Dirt diameter	5 cm
Dirt area	19.64 cm^2
Dirt volume	137.4 cm^3 or 0.14 L

Table 2 Electrical components and corresponding current consumption.

Component	Running time (%)	Current drawn (mA)
Microcontroller	100	50
Power LED	100	92.2
Switch	–	0.2
Wheel Motor	100	900
Ultrasonic Sensors (4)	100	60
Total	–	1102.4

Battery specification: Nominal Voltage = 3.7 V.
Nominal Capacity = 2200 mAh.
Charging Capacity = 4.2 ± 0.05 V.
Standard Charging Time = 3 h.
Total current consumption is 1102.4 mA.
Total Battery capacity is 2200 mAh.
Running time of the robot = 2200 mAh/1102.4 mA, ~2 h.

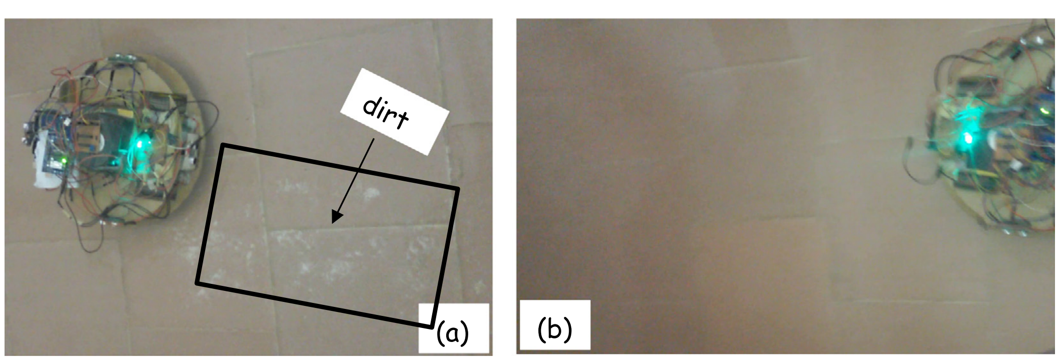

Fig. 6 Snapshot of the floor (a) prior to cleaning (b) after cleaning.

4. Conclusions

A vacuum cleaner robot has been designed, fabricated and tested. It has a disk-shape, sucks dirt via a retractable dustbin on top of which a cooling fan is mounted. The suction fan helps create vacuum that attracts dirt to the dustbin. The robot navigates with a front caster wheel and two rear wheels, and detects obstacles using the ultrasonic sensors. It is powered by 28.8 V DC battery, and works continuously for two hours when the embedded battery is fully charged.

Appendix A

Source Code

```
#include <NewPing.h>

#define MAX_DISTANCE

#include <Servo.h>

#include <AFMotor.h>

inttrigarr[] = {49,22,53,33};

intechoarr[] = {48,24,52,32};

AF_DCMotormLeft(2,MOTOR12_64KHZ);

AF_DCMotormRight(1,MOTOR12_64KHZ);

AF_DCMotorsweeper(4,MOTOR34_64KHZ);

intsetspeed = 90, servoAngle = 90,  d =0, int d =0, intrvar = 999, intlvar = 999 ,destination = 0, isReady = 8, notReady = 7, tvar = trigarr[0], evar = echoarr[0], safeD = 30;

boolisTurning = false, isPingLeft = false, isPingRight = false, initialized = false, tempAction = false, decide = false, kill = false,

doublexvar;

void setup() {

Serial.begin(115200);

sweeper.setSpeed(40);

pinMode(45,OUTPUT);

pinMode(isReady,OUTPUT);

pinMode(notReady,OUTPUT);

mLeft.run(RELEASE);

mRight.run(RELEASE);}

void loop(){

digitalWrite(notReady,LOW);

digitalWrite(isReady,LOW);

if(xvar<= (safeD/2))     {

isTurning = false;

brake();    }

else   {

tvar = trigarr[3];

evar = echoarr[3];    }} } } }

else {

digitalWrite(notReady,HIGH);

if((xvar< 7 &&xvar != 0) || tempAction)  {

tvar = trigarr[3];

evar = echoarr[3];

if(xvar< 7)   {

if(tempAction) {

tempAction = false;

decide = true;   }

else {

              kill = true;  } }

else  {

backw();

tempAction = true;  }  }

else {

tvar = trigarr[3];

evar = echoarr[3];

if(xvar< 7 &&xvar != 0)  {

decide = true;  }
```

```
NewPingsonar(tvar, evar, MAX_DISTANCE);
delay(50);
unsignedintuS = sonar.ping();
Serial.print(uS / US_ROUNDTRIP_CM);
Serial.println("cm");
xvar = uS / US_ROUNDTRIP_CM;
mRight.setSpeed(setspeed -10);
mLeft.setSpeed(setspeed);
if (kill)  {
brake();
digitalWrite(45,LOW);
sweeper.run(RELEASE);
digitalWrite(isReady,LOW);
digitalWrite(notReady,LOW);  }
else  {
if(!decide)  {
if (initialized)   {
digitalWrite(45,HIGH);
sweeper.run(FORWARD);
digitalWrite(isReady,HIGH);
if ((xvar>safeD || xvar == 0 ) && !isTurning)     {
tvar = trigarr[0];
evar = echoarr[0];
forw();   }
else    {
Serial.print("sensor switched");
brake();
if(destination == 1)     {
else {
backw();
tempAction = true; } } } }
else {
if(rvar == 999) {
tvar = trigarr[1];
evar = echoarr[1];
rvar = xvar; }
else {
tvar = trigarr[2];
evar = echoarr[2];
lvar = xvar;
if(lvar>rvar) {destination = 2;}
else  { destination = 1; }
decide = false;
        initialized = true;  } }}
if(xvar == 0 || xvar> 30) { forw();}
else {
backw();}}
voidforw(){
if(servoAngle == 90) { } else {
myservo.write(90);
servoAngle = 90; }
setspeed = 90;
mLeft.run(FORWARD);
mRight.run(FORWARD);}
voidbackw(){
if(servoAngle == 90)  { } else {
```

```
isTurning = true;
tvar = trigarr[1];
evar = echoarr[1];
if(xvar<safeD)  {
kill = true;     }
else   {
tvar = trigarr[3];
evar = echoarr[3];
right();
if(xvar<= (safeD/2))   {
isTurning = false;
brake();    }
else  {
tvar = trigarr[3];
evar = echoarr[3];  }  }  }
else   {
isTurning = true;
tvar = trigarr[2];
evar = echoarr[2];
if(xvar<safeD)   {
kill = true;     }
else     {
tvar = trigarr[3];
evar = echoarr[3];
right();
myservo.write(90);
servoAngle = 90; }
mLeft.run(BACKWARD);
mRight.run(BACKWARD);}
void left(){
if(servoAngle == 45) {  }else {
myservo.write(45);
servoAngle = 45; }
setspeed = 120;
mLeft.run(RELEASE);
mRight.run(FORWARD);}
void right(){
if(servoAngle == 135){ } else{
myservo.write(135);
servoAngle = 135; }
setspeed = 120;
mLeft.run(FORWARD);
mRight.run(RELEASE);}
void brake(){
mLeft.run(RELEASE);
mRight.run(RELEASE);
}
```

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