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Cost Effective Surface Disruption Detection System for Paved and Unpaved Roads

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ABSTRACT Roads are exposed to road surface disruptions (RSD) because of erosion, poor water drainage, rain, and soil quality. A delay in maintenance results in severe road damage that blocks the traffic for several days. Up to now, RSD detection on unpaved roads is done manually or reported by drivers. Conversely, different techniques have already been proposed for paved roads, such as vibration, image, and laser scanning. Unfortunately, the methods proposed for paved roads are not directly applicable for unpaved roads due to constraints and properties of RSD and pothole on unpaved roads. Therefore, this paper proposes a novel and low-cost method of detecting RSD based on ultrasonic sensors. The suggested model uses, as input data, relative distances collected by ultrasonic sensor beams, compute the approximate potholes and bumps on surfaces and outputs 2-D surface state map. This innovative and applicable approach has been tested on unpaved and paved roads and showed an accuracy of 94% regarding pothole characteristics (size, surface, and depth) on both paved and unpaved roads. A pothole detection rate of 62% was achieved on the paved road. Furthermore, the implemented algorithm is adaptable through a number of thresholds along with the desirable surface-sensor distance, the required RSD, the sensor's velocity, and the distance between measurements. The results showed that the system could detect RSD and give valuable information which can help the maintenance team to plan for repair.

INDEX TERMS Hump, pothole, road surface disruption, ultrasonic sensors.

I. INTRODUCTION

Road network quality is a significant factor in the economic development and well-being of the people in a nation [1]. Every year, after the rainy season, unpaved roads are subject to road surface disruptions (RSD) due to erosion, poor water drainage, and soil quality [2], [3]. Only 47.19% of roads in the world are paved [4], the unpaved roads undergo severe road degradation during the rainy season. In developed countries, vast sensor network and surveillance cameras help to monitor and detect RSDs on paved roads. However, road maintenance agencies in developing countries continue to collect RSDs data manually. Manual methods involve extensive human resources and budget. A delay in road maintenance causes severe road degradation that blocks the traffic for several days.

Researchers have proposed several methods to detect RSDs and potholes, these methods can be categorized as vibration method [1], [5]–[7], laser-scanning method [8], and vision-based method [9]–[12]. Each of the above methods comes with advantages and limitations. The vibration method can be implemented at a low cost, but the detection range is only limited to the paths of the vehicle's wheels. Whereas, any pothole or RSD outside the wheels' range is ignored; on the other hand, laser scanning method and vision-based methods can detect potholes in a wide range but the cost of the required material is high.

The methods proposed in the literature, mainly consider paved roads [5] [8], [10], [11], [13], [14]. The following requirements found on unpaved roads make the existing road monitoring systems to be unfit for the unpaved road:

1. Lack of smoothed road: the smoothness on paved roads is a key factor that helps to set a threshold for detecting abnormal section on the road; on the other hand, the smoothness of unpaved roads is not guaranteed. The road can present

different shapes depending on the soil composition (rocks, sand, mud or a mixture of the three) thus creating a problem for reference base and a threshold for classifying a place as a pothole.

2. Image based monitoring system tends to detect an unusual pattern on a given surface; references need to be provided in order to find out the areas colored differently [9], [10]. However, unpaved road lack road marking, lines, and road color is not constant.

Fig. 1 presents a portion of the unpaved muddy road.

FIGURE 1. **Unpaved road deterioration.**

As shown in Fig. 1 apart of classifying a place as defective, it is necessary to provide the profile of the road to judge the severity and the proper maintenance for that section of the road. A rapid and low-cost method for RSDs is crucial for developing an efficient RSDs scheme for paved and unpaved roads. In addition, a system that can collect RSDs information at high speed over a wide range is needed, to detect and to plan for repair in record time. The existing manual methods which are used together with the vibration-based, laser scanning-based, and vision-based methods are not sufficient to manage RSDs on unpaved roads.

The goal of this research is to develop an RSD detection method based on standard ultrasonic sensors to discover road damage on unpaved and paved roads. Low cost and high accuracy are two parameters which are targeted in the proposed system. We surveyed different materials which can calculate range between a sensor and the ground, and we concluded that the Ultrasonic sensor fitted well to collect data for road surface disruption. As a result, the service in charge of road control and management will get enough data to judge the condition of the road and decide where and when to repair it.

In this research, we are proposing a novel RSD system using ultrasonic sensors to detect damage on paved and unpaved roads. The proposed system is mounted on the rear part of the vehicle and collects information about road surface disruption. The collected data are preprocessed by the RSD system before they are sent to a server for final processing. An algorithm is proposed which evaluate the road damage and the information is transmitted to road management service. The proposed RSDs detection algorithm is designed considering paved and unpaved road structures. The algorithm was tested on an Arduino Mega 2560 with PC-based software.

II. RELATED WORK

Several efforts have been made for developing methods which can detect RSDs. Existing methods can be classified into vibration-based method [1], [5]–[7], laser-scanning method [8] and vision-based method [9], [10]–[12]. The accelerometer is the key element in vibration-based methods for RSDs and pothole detection. The major advantage of the vibration-based method is the low cost of the materials and the simple algorithm implementation [1]. Accelerometers in mobile phones are collectively used to detect RSDs and potholes, in Gónzalez *et al.* [5], Aksamit and Szmechta [6], and Jamakhandi and Srinivasa [15] proposed a system where the RSDs are monitored by a citizen car using the mobile phones' acceleration sensing capabilities, and they identify and tag the presence of the RSDs. One drawback of the vibration-based method is the low accuracy which remains a challenge to consider when using it [9]. Some improvements have been made in order to increase accuracy in the vibration-based method, in Wang *et al.* [7] proposed a real-time pothole detection method based on mobile sensing to collect and normalize the accelerometer data from the mobile device for free angle, thus improving the accuracy of the vibration-based method.

Li *at al.* [14] used the dynamics of hitting potholes by an automotive and divided the process into several phases to capture the responses of hitting a pothole. Considering the context of unpaved roads, the accelerometer-based technique suffers from the following drawbacks:

1. Vibrations are frequent on unpaved roads; false alerts are likely to happen; in fact, more damaged places are likely to produce low vibration due to the fact that the drivers reduce speed accordingly whenever they approach a damaged place, the more serious the damage is, the less vibration is likely to happen.
2. Damage in the road is detected whenever one of the wheels traverses the damaged place, the RSDs between the wheels are ignored [10].
3. The drivers are likely to avoid hole and RSDs in order to protect their vehicle from damage.

High-speed cameras with high resolution have been recently introduced to automate road inspection, Medina *et al.* [11] presented an approach to detect cracks in the pavement of the road combining visual and geometrical information using a combination of 2D and 3D images. Ryu *et al.* [10] introduced a method based on two-dimensions (2D) images wherein an optical device is mounted on a vehicle and collects images, and the collected data are sent to a pothole algorithm for processing. Kang and Il Choi [12] presented a new approach based on 2D LiDAR and camera. The proposed method is not affected by the electromagnetic wave and the surface state. The 2D LiDAR algorithm includes noise reduction, thus improving the accuracy of pothole detection.

Laser scanning method collects high amount of data and is able to recreate the road profile. Yu and Salari [8] presented an approach based on laser imaging for pothole detection and severity measurement. They used the laser line in the pothole area to determine the contour of the deformed pattern. The proposed approach is not subjected to image shadow. Laser scanning method produces the highest accuracy in RSDs; the main argument against this method is the high cost of sensors and maintenance [1], [9], [10], and the method is not efficient for fast pothole detection in wide area [9].

Though the image-based method is considered to be a low-cost solution, there are some drawbacks regarding the capacity to discern between the different classes of defects and the needed computing power. Moreover the image-based technique can only operate during daytime under good weather condition in order to increase the quality of the images. The vibration-based method is a very low-cost solution but could provide wrong results on unpaved roads. The laser-based method is considered to have high accuracy. However, the cost of laser scanning equipment is significantly high. Indeed, the above methods cannot support RSDs and pothole detection efficiently on unpaved roads. The following arguments support our idea:

1. A pothole on unpaved roads may cover a wide area (several meters in diameter).
2. Unpaved roads have different patterns regarding the quality of the soil. Hence new parameters should be considered for each road.
3. RSDs on unpaved roads can have different patterns; some of them cannot be detected by both image-based and vibration-based methods.

The three arguments above motivated the current study. Thus, the following hypotheses are made:

H1: The RSD detection system can improve the potholes detection rate.

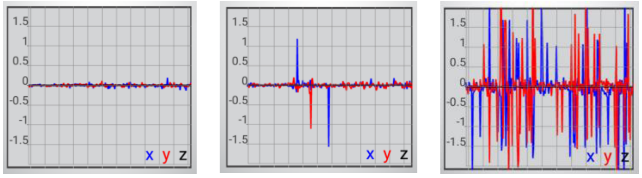
H2: The RSD detection system can monitor both paved and unpaved roads.

Therefore, in this paper, we propose an RSD and pothole detection system for paved and unpaved roads using ultrasonic sensors. Furthermore, an algorithm is designed to fit the proposed system. Our RSD and pothole detection system is a low-cost system and can guarantee high accuracy. The contributions of this paper are twofold:

1. First, we present the problems related to unpaved road monitoring process, the lack of leveled road which is a factor to consider when monitoring unpaved roads.
2. Second, we propose an RSD and pothole detection system which takes into account the characteristics and patterns of paved and unpaved roads.

It is imperative to mention here that the literature schemes, which consider only pothole detection on paved roads, are not applicable to unpaved roads. In illustration of the inapplicability of vibration-based method on an unpaved road, an experiment is performed on both unpaved and paved roads using a mobile phone accelerometer; results are presented in Fig. 2 where 80% of the unpaved road is classified as defective.

Furthermore, unlike existing solutions that consider only pothole detection and crack detection, the proposed solution jointly detects pothole, cracks, and other kinds of RSDs (ruts). The surface covered by the RSD is also estimated; as a result the proposed solution can be applied on both paved and unpaved roads.



(a) (b) (c)

FIGURE 2. Accelerometer results on paved and unpaved roads. (a) Normal paved road. (b) Paved road with one pothole detected. (c) Normal unpaved road.

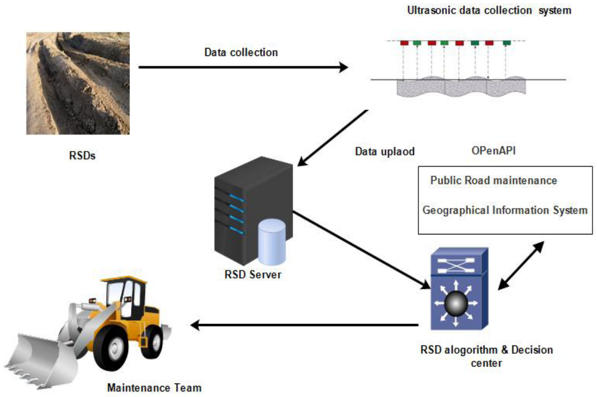


FIGURE 3. RSD detection system.

III. RSD MAINTENANCE SYSTEM

A. SYSTEM DESCRIPTION

This system is designed to gather information about RSDs through ultrasonic sensors mounted on the rear of a vehicle. Our algorithm is applied to the collected data to detect RSDs. More information about the RSD is collected: size, depth, surface, and location. The collected data are stored onboard in the detection system before it is forwarded to RSD server where the maintenance service uses the collected data to obtain road condition. The RSD detection device was designed in a way that it can be mounted on any type of vehicle, and was given the capabilities of operating offline, thus reducing the reliance to the RSD server. Fig. 3 portrays the RSDs detection system used in this study.

1. The ultrasonic sensors: It is a set of sensors used to collect data about the distance from the ultrasonic system and the surface. They scan and send the values to the microcontroller according to their internal clock.
2. An accelerometer module: The ultrasonic system is mounted on a vehicle whose velocity affects the frequency of data collection and then the scanning distance. The accelerometer averages the speed of the vehicle and sends speed values to the microcontroller

which adjusts the scanning frequency accordingly. The objective is to harvest data at a constant distance regardless of the vehicle's velocity.

3. The GPS module: This module is responsible for collecting information related to the pothole location. The pothole location is used to design the surface disruption map.
4. The gyroscope module: This module controls the tilt of the scanning device and sends the information to the microcontroller which adjusts the collected values accordingly.
5. The microcontroller: It is the core module of the system which centralizes information from all aforementioned module and has the algorithm to compute output data for end users.

B. RSD MODEL INPUTS AND OUTPUTS

1) MODEL INPUTS

According to the ultrasonic system, input data are:

1. Ultrasonic wave speed (v_sensor).
2. Time the ultrasonic wave takes to propagate from the transmitter to the object and then back to the receiver (tTOF).
3. Number of sensors.
4. Vehicle speed.

2) MODEL PARAMETER

1. Disruption resolution: number of measurements per unit of length (n_measmt).
2. The normal distance between the sensor and the surface (d_level).
3. The distance between the ultrasonic sensors (d_sensor).
4. The frequency of disruption processing.

3) MODEL INTERMEDIARY DATA

1. Measurements frequency.
2. The actual distance measured by the sensor from the surface (d_actual).

4) MODEL OUTPUTS

1. Disruption 2D measurements: length, depth and surface.
2. Disruption location and surface geo map.

The RSD detection system is composed of several modules as shown in Fig. 4:

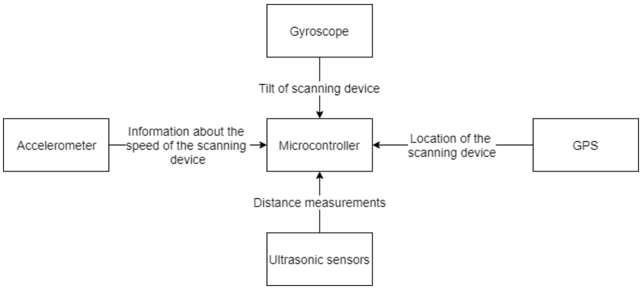


FIGURE 4. RSD modules.

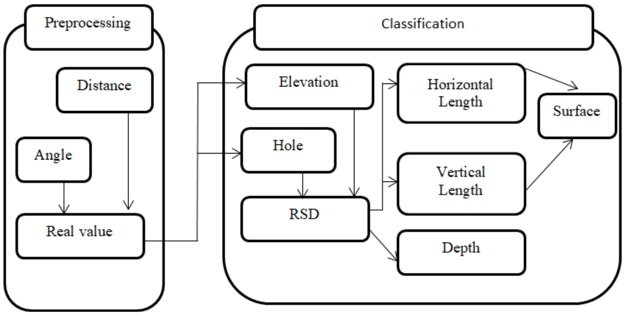


FIGURE 5. RSD flowchart.

C. RSD FLOW CHART

The proposed method for RSD detection can be divided into two steps: Preprocessing and classification as shown in Fig. 5. First, the raw data are collected by the sensors (distance of the sensor from the ground and the slope of the sensor during measurement), next an actual distance is computed from the raw data collected in the previous step. We then compare the values from step one to a threshold to decide whether the collected values are normal or not. Finally, if the values fall outside the threshold value, information such as horizontal length, vertical length, depth, and the surface of the RSD is computed.

D. PREPROCESSING

1) FREQUENCY OF MEASUREMENT

Before we can compute the measurements, we need to compute the frequency of measurements. It will be computed from the desired pothole resolution (n_measmt) and the vehicle speed. Suppose we need four measurements per meter with a vehicle's speed of 3.6km/h (1m/s). The measurements will be triggered at the frequency of 0.25 second as presented in algorithm 1.

Algorithm 1 Frequency of Measurements

```
Input: n_measmt, velocity, distance
Output: time
time = $\frac{distance}{velocity * n\_measmt}$
Return time
```

2) ACTUAL SENSOR-SURFACE DISTANCE

Distance measurement using ultrasonic waves have been used in broad applications: robot control, factory automation, liquid level [16], and road monitoring. Madli *et al.* [17] used ultrasonic sensors to detect potholes and humps, the ultrasonic sensor is positioned under a two-wheeler (motorbike) and collects distance between the sensor and the ground, the distances collected are later used to detect potholes and humps on the road. Taniguchi *et al.* [18] performed a similar study where the ultrasonic sensor is positioned on the handlebar of a cycle; the ultrasonic wave can detect the 223 cm away obstacle. In the two cited research, only one sensor is used; the proposed RSD detection system is composed of an array of ultrasonic sensors which measure the distance between the RSD detecting device and the ground (road), the device is attached on the rear part of the vehicle at distance d_level (say 50cm) above the road level. Consequently, for a normal road without surface disruption, the ultrasonic sensors are expected to return a measure of d_level (50cm). The distance between the sensor (transmitter) and the object can be computed by the following formula [19]:

$$\mathrm{d\_actual} = \mathrm{v\_sensor} * \mathrm{tTOF}/2 \tag{1}$$

With:

- v_sensor the ultrasonic wave speed and

- tTOF the time the wave takes to propagate from the transmitter to the object and then back to the receiver. Fig. 6 shows the DSR data collection system.

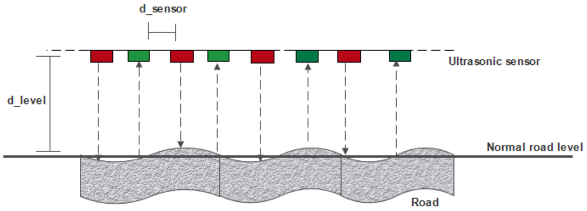


FIGURE 6. Data collection (Front view).

3) ANGLE MEASUREMENT

In some situation, data may be collected on surfaces which are not flat, thus creating a slope in the RSD detection device. False measurements are collected and may provide false information about the RSD. Fig. 7 sketches the measurement is taken on a slope with an angle α. The slope on the road produces an error in the measurement β which can be computed by the sine function. In a right triangle, the sine of an angle α is the length of the opposite side (β) divided by the length of the hypotenuse (H).

$$\beta = \mathrm{H} * \mathrm{Sin}(\alpha) \tag{2}$$

The error β is computed for each sensor and is reduced or added to the measurement depending on the position of the slope.

$$\mathrm{d}_\alpha = \mathrm{v} * \frac{\mathrm{tTOF}}{2} \pm \beta \tag{3}$$

The collected data can be presented in a grid where each measurement is composed of four parts:

1. The sensor position in the DSR collection device 1 . . . n_sensor where n_sensor is the number of sensors.
2. A unique id 1 . . . n_measmt which is incremented for each measurement.
3. The value collected by the sensor.

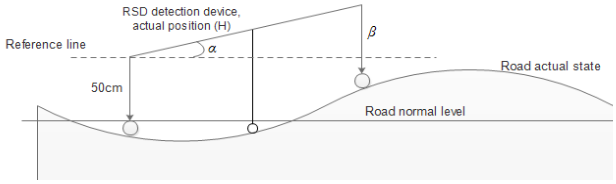


FIGURE 7. Slope consideration during measurement.

4. The GPS location.

The data are stored in a list as presented in Algorithm 2 as follow:

Algorithm 2 Data Storage

```
Input: n_measmt,n_sensor,value
Output: list
for id = 1 to n_measmt
    for sensor = 1 to n_sensor
        list.append(id,sensor,value,GPS_location)
return list
```

E. CLASSIFICATION

After preprocessing, the classification step is performed to decide whether the measured value falls into one of the following case: normal, hole, elevation. When a specific surface (called a dot in this study) has been classified as normal, hole, or elevation, more information such as horizontal length, depth, and location are needed to be collected. The following steps are performed by the RSD system for classification and decision making:

1. Detect all abnormal dots;
2. Connect the neighbor dot;
3. Compute the diameter of the disrupted surface;
4. Detect the highest/deepest value in the disrupted surface; and
5. Compute the area covered by the disrupted surface.

1) ABNORMAL DOTS

Abnormal dot detection is done by a three queues mathematical string function ‘‘dot_classifier’’ as follows:

$$\mathrm{dot\_classifier(x, y, z)} = \left\{ \begin{array}{c} \text{hole if}(\mathrm{x} - \mathrm{y} < \mathrm{z}) \\ \text{normal if}(|\mathrm{x}\text{-}\mathrm{y}|) = z) \\ \text{hole if}(\mathrm{x} - \mathrm{y} > \mathrm{z}) \end{array} \right\} \tag{4}$$

With:
x = d_level (the desired level)
y = d_actuer (the actual measured level)
z = the threshold

2) NEIGHBOR DETECTION

The proposed algorithm traverses the data from left to the right; the data are collected in the form of a grid. When a dot is lower or higher than the threshold, a new ID is generated and assigned to that dot, the algorithm checks if the point has a neighbor, if so, the dot shares its ID with the neighbors with a value higher or lower than the threshold. The process of checking for neighbors is presented in algorithm 3.

Algorithm 3 Find Neighbor

```
Input: dot
Output: neighbors
Set threshold
direction:right,u
has_neighbor
foreach dir in direction
    neighbor = dot + dir
        if value(neighbor) <> threshold then
            neighbors.append(neighbor)
return neighbors
```

Algorithm 3 finds the neighbors of each dot, a dot B is considered as a neighbor of dot A, if A and B have values different to threshold and B is directly connected to A. Algorithm 4 searches for all neighbors and adds them into a list with a unique ID.

Algorithm 4 Search Neighbors

```
Input: all_dots
Set threshold
Output: dot IDs
foreach dot in all_dots:
    if dot <> threshold
        if dot.id is NULL
            if has_neighbors(dot) is NUL
                generate new id for dot
             else
                dot.id = neighbor.id
return dot IDs
```

Algorithm 4 provides ID to dot, dots which are directly connected share the same ID.

The classified data can be rendered on the road as shown in Fig. 8. The top view of the data arranged as a grid, the red spots in the road represent the dots on the road with a value higher or lower than the threshold. On this surface, lines (A to F) represent the sensors and columns (1 to n) represent measurements.

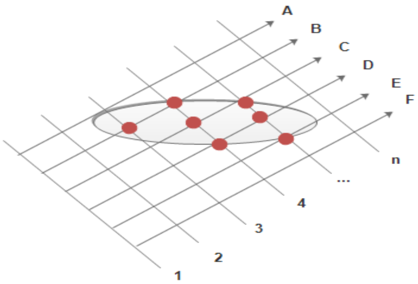


FIGURE 8. Data (top view).

3) DEPTH OF THE RSD

The dot with the highest value is selected as the depth of the pothole as presented in algorithm 5.

Algorithm 5 Depth of the Pothole

```
Input: ID
Output: depth
depth = 0
foreach dot with id = ID:
    if dot.value> depth then
        depth = dot.value
return dept
```

Algorithm 5 compares the depth of dot with the same ID. The dot with the highest value is considered as the depth of the pothole.

4) SURFACE COVERED BY THE RSD

Each sensor has a position on the RSD device, the first sensor has position 1, and the last sensor has position n_sensor, where n_sensor is the total number of sensors. Each scanned row has a unique ID ranging from 1 to n_measmt where n_measmt is the total number of measurements. Thus, any dot can be represented by a value from the matrix n_sensor x n_measmt. In order to compute the diameter of a pothole, we need the far East, far West, far South and far North dots of the pothole. Algorithm 6 shows how the four values are computed.

Algorithm 6 Diameter of the Pothole

```
Input: pothole ID
Output: horizontal_distance, vertical_distanc
width = 0, length = 0, East = 0, West = n_sensors,
South = n_measmt, North = 0, Length = 0,Width = 0
foreach dot with id = ID:
    if dot.position<West then West = dot.position
    if dot.position>East then East = dot.position
    if dot.location >South then South = dot.position
    if dot.location <North then North = dot.position
horizontal_distance = (East-West)+1
vertical_distance = (North-South)+1
return horizontal_distance and vertical_distance
```

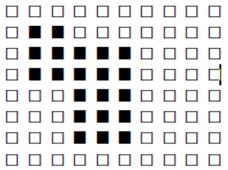
Fig. 9 shows a pothole and the distances computed using algorithm 6.

The pothole dots are represented by the black squares (■) and the normal dots are represented by the white squares (☐).

Algorithm 7 computes the surface covered by the pothole.

Fig. 10 shows a pothole, and the surface computed using algorithm 7.

In this algorithm, a square is composed of four dots.



(a)

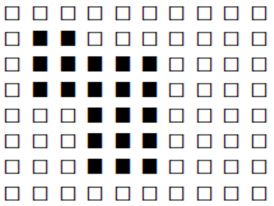
```
South:   6
North:   1
East:    1
West:    5
Vertical_distance:   6
Horizontal_distance: 5
```

(b)

FIGURE 9. Horizontal and vertical distance of the pothole.

Algorithm 7 Surface of the Pothole

```
Input: vertical_distance,horizontal_distance
Output: surface
all_dots = vertical_distance * horizontal_distance
all_squares = vertical_distance-1 * horizontal_distance-1
pothole_square = all_squares-(al_dots-threshold_dots)
return pothole_square
```



(a)

```
South:  6
North:  1
East:  1
West:  5
Vertical_distance: 6
Horizontal_distance: 5
all dots:  30
dots in threshold:  21
Total number squares:  20
Pothole squares  11
```

(b)

FIGURE 10. Surface estimation of the pothole.

IV. PERFORMANCE EVALUATION

A. EXPERIMENTAL ENVIRONMENT (UNPAVED ROAD)

In this study, measurements have been collected by ultrasonic sensors attached to the rear of a vehicle. The RSD device is composed of 20 sensors separated by a distance of 10 cm, thus giving a scanning area of 200cm as shown in Fig. 11. The recorded values are saved in a text format in an 8 GB SD card memory. The ultrasonic sensors, the gyroscope and the GPS module are controlled by an Arduino mega 2560, the first step of data processing is performed by the Arduino. The last step is done in Python on a laptop (Intel Core i5, 2.67GHz, 4 GB RAM). The python script displays the pothole detection results and other relevant information such as width, height, depth, surface, and location. For continual road scanning, the road was divided into frames of 20 rows.

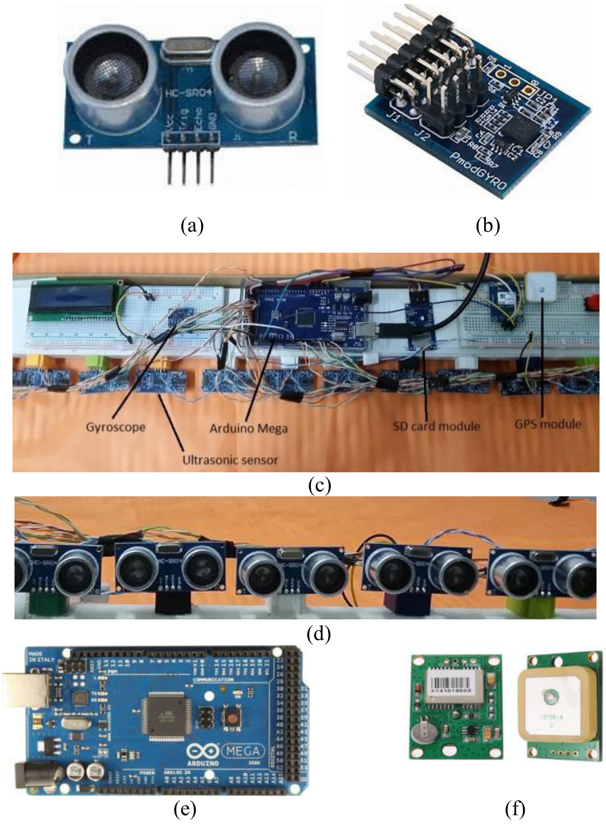
Table 1 details the values of the parameters used in this study. The parameter can be varied according to the road condition and the expected result by the user.

TABLE 1. Parameters used in this study.

Parameter	Value
number of sensors	20
frame size	20
scanning distance	0.1m
threshold	0

The following materials depicted in Fig. 9 have been used to test the system.

Considering the materials used in this study as presented in Fig. 11, we believe that we have achieved our first goal of building a low-cost RSD detection system. The cost of these components is under one hundred dollars (USD).



(a) (b) (c) (d) (e) (f)

FIGURE 11. Materials used in this study. (a) Ultrasonic sensor. (b) Gyroscope. (c) Detection device front side. (d) RSD device top side. (e) Arduino mega. (f) GPS module.

1) RESULT

Fig. 12 shows an unpaved road portion, the algorithmic result and a 2D representation of the RSD. A summary for a frame area of 400 dots (20 sensors for 20 recordings) is presented;

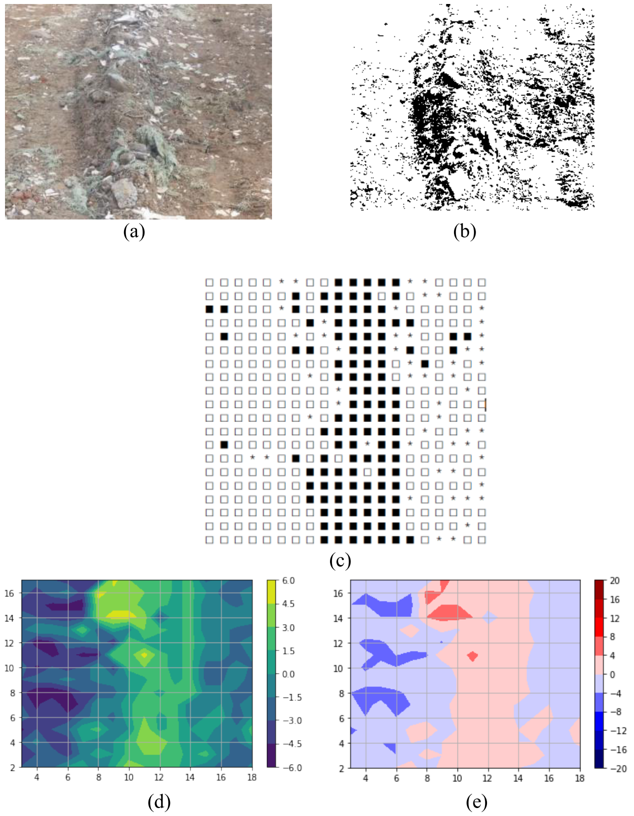


FIGURE 12. Frame summary. (a) Frame image. (b) Frame image in black and white. (c) Algorithm result. (d) 2D image detailed. (e) 2D image summarized.

the number of potholes, the ID of each pothole is given in the frame summary.

With:■: elevation, □: holes, ∗: normal areas.

The threshold can be changed according to the acceptable state by the public road maintenance; Fig. 13 presents the results of our algorithm for threshold ranging from 0 to 5cm.

With: (■) elevation, (□) holes, (+) normal areas.

Fig. 13 shows that we can set the sensitiveness of the system by setting the threshold to a desirable value.

2) PERFORMANCE

In order to judge the accuracy of the proposed method, we manually measured the parameters of five RSD, and the results were compared with the values generated by the system. The results are presented in table 2.

TABLE 2. Manual measurement versus system measurements.

ID	Manual measurements			System measurements		
	Depth	Width	Length	Depth	Width	Length
1	3.1cm	0.7cm	60.2cm	3.1cm	0cm	60cm
2	2.0cm	30.0cm	10.7cm	2.0cm	30cm	10cm
3	3.3cm	30.6cm	20.4cm	3.1cm	30cm	20cm
4	3.0cm	30.1cm	20.0cm	3.0cm	30cm	20cm
5	2.2cm	10.3cm	20.1cm	2.0cm	10cm	20cm

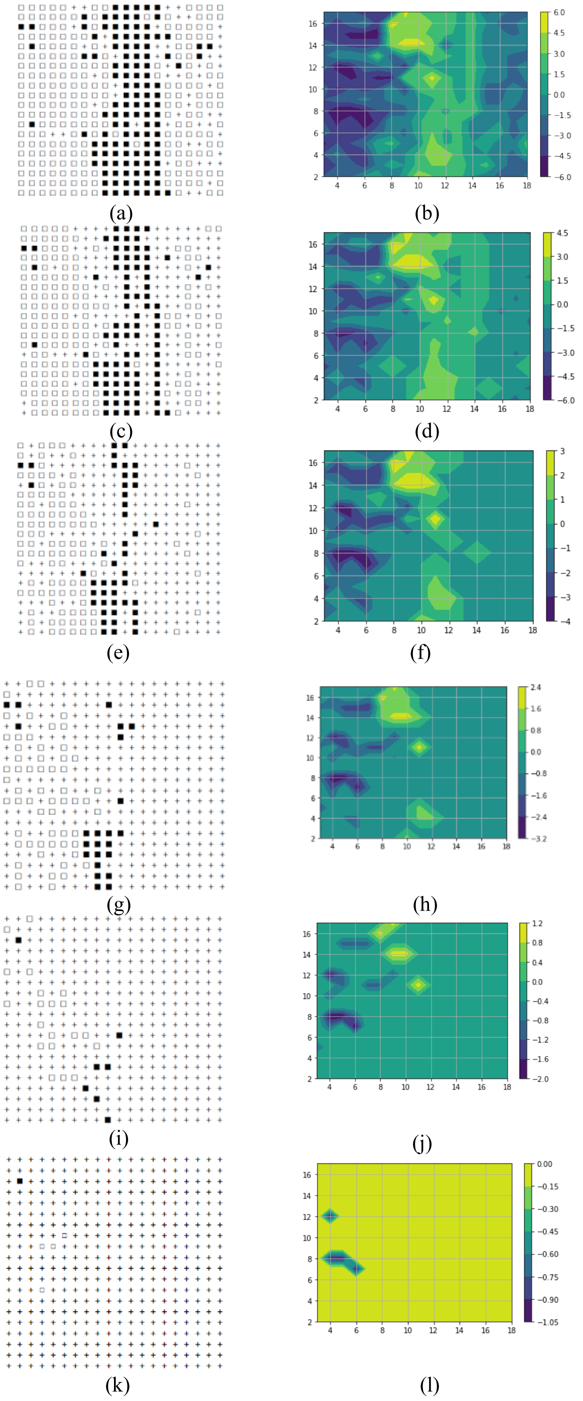
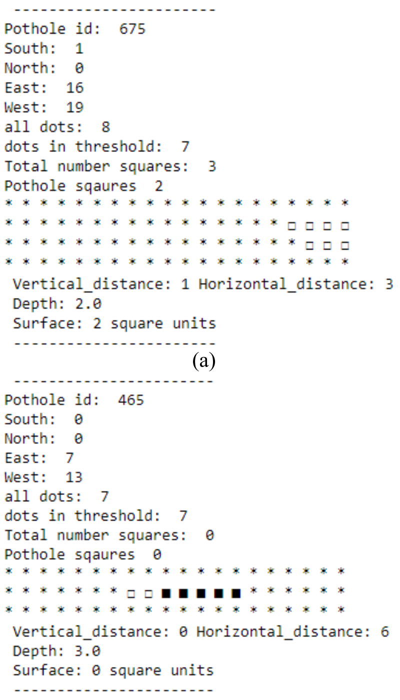


FIGURE 13. Algorithm results for different thresholds. (a) Threshold 0cm. (b) Threshold 0cm 2D image. (c) Threshold 1cm. (d) Threshold 1cm 2D image. (e) Threshold 2cm. (f) Threshold 2cm 2D image. (g) Threshold 3cm. (h) Threshold 3cm 2D image. (i) Threshold 4cm. (j) Threshold 4cm 2D image, (k) Threshold 5cm. (l) Threshold 5cm 2D image.

As shown in table 2, the proposed method has an overall accuracy of over 90% for the length and the width. The accuracy can be increased by reducing the distance between the rows during data acquisition. The depth has an accuracy of 94%; the ultrasonic sensors measure the distance with high precision. In this study, we considered a distance of 10 cm between the ultrasonic sensors and a distance of 10 cm between two measurements. Fig. 14 gives more details about the RSD with width or length equals zero. For RSD with width or length equals to zero, the surface was not approximated, they are considered as cracks, and still, the depth was computed with precision.



```
 ----------------------
Pothole id:  675
South:  1
North:  0
East:  16
West:  19
all dots:  8
dots in threshold:  7
Total number squares:  3
Pothole sqaures  2
* * * * * * * * * * * * * * * * * * * *
* * * * * * * * * * * * * * * * □ □ □ □
* * * * * * * * * * * * * * * * *  □ □ □
* * * * * * * * * * * * * * * * * * * *
 Vertical_distance: 1 Horizontal_distance: 3
 Depth: 2.0
 Surface: 2 square units
 ----------------------
```

(a)

```
 ----------------------
Pothole id:  465
South:  0
North:  0
East:  7
West:  13
all dots:  7
dots in threshold:  7
Total number squares:  0
Pothole sqaures  0
* * * * * * * * * * * * * * * * * * * *
* * * * * * * □ □ ■ ■ ■ ■ ■ * * * * * *
* * * * * * * * * * * * * * * * * * * *
 Vertical_distance: 0 Horizontal_distance: 6
 Depth: 3.0
 Surface: 0 square units
 ----------------------
```

(b)

FIGURE 14. **RSD with zero width or zero length.(a) Pothole with width and length different to zero. (b) pothole with width equals to zero.**

Single line abnormal dots are not sufficient for disruption classification since a hole is not a single line but a set of connected dots with more than one line. The results presented in this section confirms part of the second hypothesis, the RSD detection approach yields good results on unpaved roads with accuracy in measurements higher than 90%.

B. EXPERIMENTAL ENVIRONMENT(PAVED ROAD)

In this section, we test the performance of the RSD on paved roads, and a comparison study is made between the RSD method and the vibration method. We simulate potholes on a paved road, a distance of 100 m is considered; ten potholes of different sizes are put randomly on the road. We implement the approach proposed by [5] and [6] where a pothole is detected whenever one of the tires hits the pothole if none the pothole is ignored. The simulation parameters are presented in table 3.

For vibration approach, a pothole is considered as detected if one of the tires hits the pothole as presented in Fig. 15. On the other hand, a pothole is detected by the RSD approach if one of the ultrasonic sensor beam hits the pothole as shown in Fig. 16.

TABLE 3. **Simulation parameters.**

	Parameters for vibration method	values
1.	Distance between tires	200 cm
	Parameters for RSD approach	
1.	Length of the scanning device	240cm
2.	Number of sensors	20
3.	Distance between sensors	12cm
4.	Distance between 2 measurements	12cm
	Parameters for pothole	
1.	Number of potholes	10
2.	Pothole size	random
3.	Pothole position	random
	Parameters for road	
1.	Road length	100m
2.	Road width	4m

TABLE 4. **Result of number of potholes detected by RSD and vibration approach.**

Round n°	RSD approach	Vibration approach
1	9	2
2	6	2
3	8	2
4	5	2
5	3	2
6	5	2
7	9	3
8	5	1
9	6	3
10	6	3
Total	62	22
Average	6.2	2.2

For the vibration approach, only pothole F is detected, the other nine potholes are out of range. For the RSD approach, potholes A, B, C, D, E and F are detected, G, H, J and K are ignored. Ten rounds are performed, where ten potholes are put randomly on the road, the number of potholes detected by each approach are presented in table 4.

The average detection rate for RSD approach is 62% compared to 22% for vibration approach. The first hypothesis is confirmed, RSD approach has a higher detection rate than the vibration approach, and the parameters of RSD approach can be tuned to increase the overall performance. The second hypothesis is once again confirmed, the RSD detection approach is suitable for unpaved road and paved road. Fig. 17. shows the detection performance of the RSD approach compared to vibration approach.

Higher performance can be achieved by increasing the number of sensors, reducing the distance between sensors and reducing the distance between measurements.

C. CHALLENGES

Acquiring information from the road helps us to judge the road condition and recreate the profile of the road. The road data are collected by ultrasonic sensors. Our system will encounter the following challenges that require further attention.

1) DISTANCE BETWEEN TWO SENSORS (d_sensor)

An RSD between two sensors with a width lower than d_sensor will not necessarily be detected. Therefore d_sensor

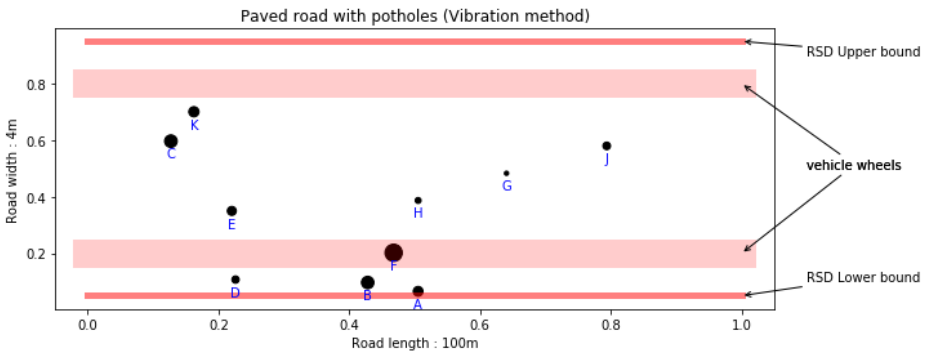


FIGURE 15. **Vibration approach, paved road with potholes.**

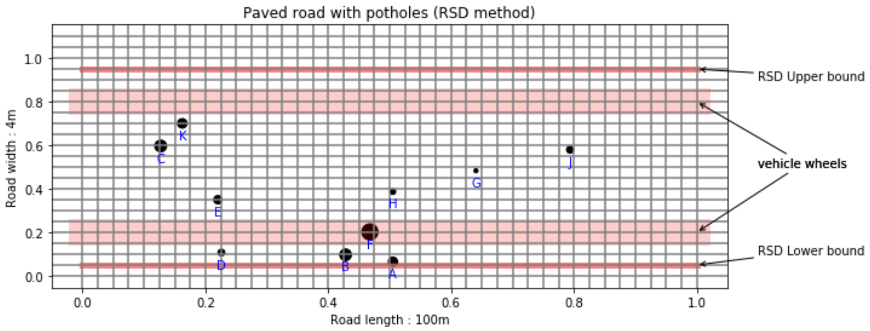


FIGURE 16. **RSD approach, paved road with potholes.**

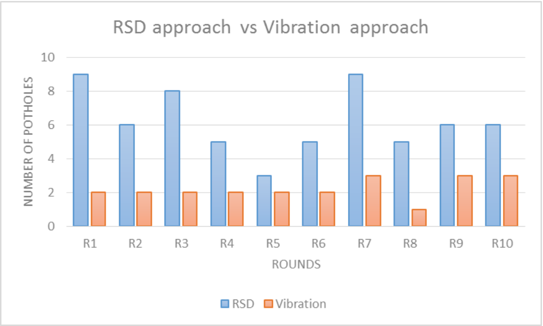


FIGURE 17. **RSD approach and vibration approach comparison.**

should be minimized to detect the maximum number of RSD.

2) DISTANCE BETWEEN TWO MEASUREMENTS (d_measmt)

An RSD between two measurements with a length lower than d_measmt will not necessarily be detected. Therefore d_measmt should be minimized to detect the maximum number of RSD.

3) LENGTH AND WIDTH

The length and the width of an RSD are computed from the distance between two dots. Consequently, the RSD portions between normal and abnormal dots are ignored.

4) POTHOLES FILLED WITH WATER

In case of a pothole filled with water, the depth was computed with error, the ultrasonic sensor just measures the distance up to the water level but not the full pothole depth.

V. CONCLUSION & FUTURE WORK

This paper focused on pothole detection system for paved and unpaved roads using ultrasonic sensors, accelerometer, gyroscope and GPS module. We designed a unique algorithm to detect RSD and potholes. The ultrasonic sensor beam is used to collect distance between the RSD scanning device and the road; the collected values are passed to the algorithm which detects the RSD. The algorithm is executed in two phases, the first step (data collection and data preprocessing) is done in a microcontroller; the second stage is performed on a computer. The proposed method was designed to detect potholes and RSD on paved roads and unpaved roads, where the requirements are different and unique for each type of road. The experimental results showed that the algorithm could detect potholes and can provide several kinds of information and parameters which are essential for the road management department.

We have mentioned some of the challenges we faced in the previous section. In our future work, we will try to increase the accuracy of the model by reducing the distance between sensors and creating several rows of sensors to minimize the distances between these sensors. The proposed system is cost effective due to the material used. This, being a preliminary study, we believed that the results are not enough to demonstrate the full performance of the system. In the future, we want to implement the system in collaboration with the road authorities of D.R. Congo to judge the full performance of the system.

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