



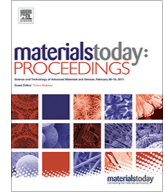
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Performance analysis of autonomous UV disinfecting robot (UV bot) using Taguchi method

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ABSTRACT

As a result of the COVID-19 epidemic, there is a growing demand for robots to perform various operations which include service bots, cleaning, and disinfection bots. Viral contamination has been one of the major causes of human fatality which has abruptly increased in this situation. Availability of existing technologies is always surpassed by an effective one so as is the UV-Bot developed in this project. This bot aims for a highly accurate percentage of up to 96.8% of germ clearance at pre-defined conditions which are user-friendly. Also, the robot is designed in a compact size and effective shape to achieve maximum efficiency. The robot is deployed in hospital pathway and rooms for disinfection whereas human detection and obstacle avoidance has been included with a custom-developed algorithm that supports autonomous navigation and corner tracking facility. The robot also supports live streaming of the disinfecting site with an emergency alarm and stop in human detection. This type of robot is highly capable of destroying viral infections at a particular point which is validated using Taguchi analysis and also the robot is 3D modelled and tested using static and dynamic obstacles. Thus UV-Bot is manually controllable or autonomous which uses the A* algorithm to store or retrieve the disinfecting site map which is recorded if used frequently.

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1. Introduction

The terms sanitisation or disinfection is used to clear harmful, disease causing germs or viruses from any particular site or area. Every day usage of hospitals and medical treatments are advancing to support human health in various departments and fields. In the same advancement the disease also spread and multiply in no mean time. Although this cannot be completely avoided or stopped experimentally, it is totally possible to keep the living environment in control by cleaning our living area. When the severity of viruses hike, the level of killing it should also hike up, so as in this project Ultra-violet radiation is used to disinfect the germ prone area. The UV-Bot aims a highly effective and optimal disinfection with minimal time consumption. This process is carried out by a custom developed algorithm with a set of hardware working in sequence to achieve the maximum accuracy. Usage of these types of robot can lower the risk of disease spread, and ensures a safe medical

period every subject goes through. Diab-El Schahawi *et.al.* [1], design and implementation of a fully autonomous and cost effective UV disinfection robot is presented which has huge potential to guard people from coronavirus by sterilizing surfaces with the help of 20 W UV lamps. The disinfection is done along a pre-defined path without human intervention as UV is deadly and dangerous to all living beings along with microbes. Apeksha Wadibhasme *et.al.* [2] Provides a detailed assessment of robot usage in the COVID –19 situation and how sanitizing can effectively help. Any disease can be effectively managed by disinfecting the environment to reduce the number of infected persons. Robots are exclusively classified using application-based categories to match every part of hospital service, covering fault-tolerant control and dependable architectures for safe and reliable operation within healthcare facilities. Srividya *et al.*, [3] discussed about the design and deployment of a completely autonomous UV disinfection robot which disinfects. UV is destructive and dangerous to all living beings, including germs, therefore disinfecting is done along the pre-defined path without human interference. The inactivation of coronavirus on the surface takes at least 1 min with the Ultraviolet

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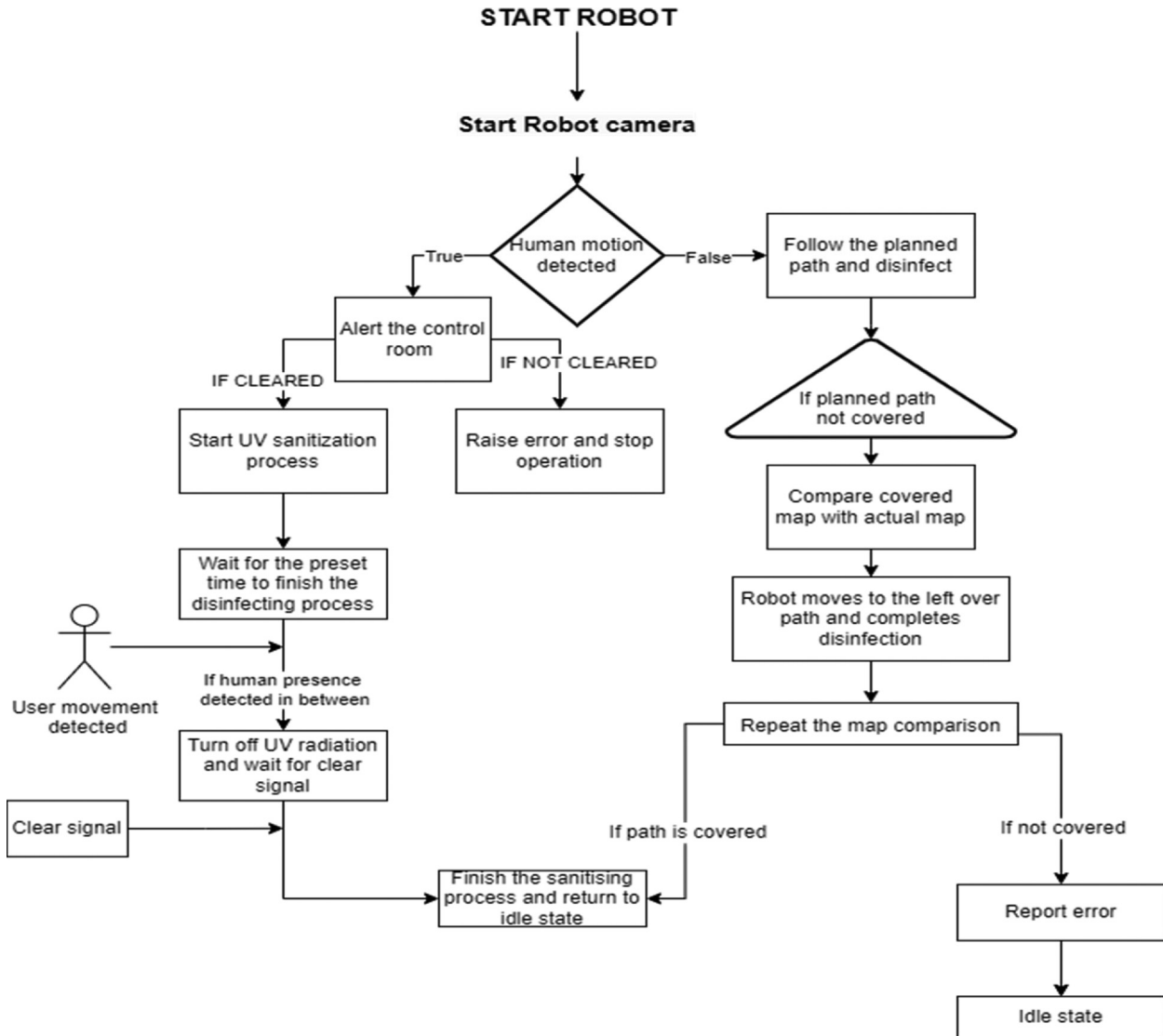


Fig. 1. UV bot algorithm flow.

robot. Human detection is as less accuracy due to usage of a single PIR sensor and the robot does not check for human in periodic intervals. Mansi Dhikle et al. [4] demonstrates a manually controller robot car using android device which does not actually contain UV lamps. The robot broadcasts live video from its surroundings. The usage of robots in this case reduces human interaction with microorganisms. The use of this robotic decreases the risk of infection, but the efficiency of the robot is to be taken under consideration. The robot may cause potential damage to the environment due to usage of limited distance measurement sensors which may result in damage of expensive devices Ipsita Jash et al., [5] produced a design and build a UV disinfection robot for use in public places such as hospitals, shopping malls, offices, and universities. By delivering condensed UV rays that damage the gene sequence of germs and prevent them from multiplying, the robot as the robot should be harmless and pleasant to humans and animals the robot is enabled with motion detection. While disinfecting the robot moves with very less accuracy as the speed of the robot is comparatively high that results in less disinfection percentage. Ayush Lokhande [6] describes the prototype of a robot moving around an area with LED- like UV lights which are not

actually UV-C band lights. This work gives a basic interface of raspberry pi with UV light and motor manual control.

2. Proposed methodology

Methodology applied in this paper comprises an algorithm for the autonomous movement of UV-C robot and most importantly identifies human presence inside the disinfecting site as the radiations are harmful to the human skin. The algorithm designed as in Fig. 1 has an accuracy of 95 % of effective germ clearance under room temperature and conditions. The optimization of the robot movement through the area of clinics or germ prone areas are carried out by A* algorithm which gives an effective surface disinfection at a minimum interval of time.

2.1. A* algorithm for trajectory plan of UV bot

A prominent node traversal trajectory planning algorithm is the A* Algorithm. A* works in a similar way to Dijkstra's algorithm, but it directs its search to the most promising areas, potentially saving a lot of time in the process. To reach the most optimal conclusion with existing data set, this algorithm is mostly utilized. Based on

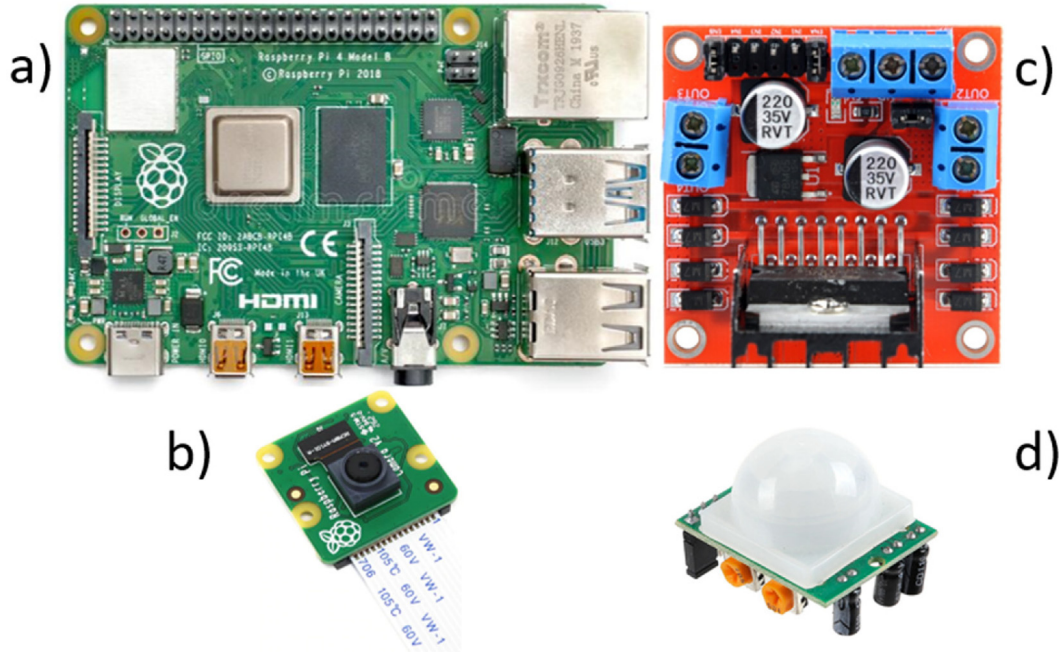


Fig. 2. Components Used in UV Bot a) Raspberry Pi b) Pi camera c) L298N motor driver d) PIR sensor.

our requirements, the base function can be customized to a given application or environment. It uses the shortest path for traversal from start to end points. To find the least expensive path the following equation is considered.

$$f(n) = g(n) + h(n) \quad (1)$$

Reason behind the selection of A* algorithm comparing D* or RRT algorithm is the accuracy that the algorithm which allows the hardware to achieve maximum efficiency in path traversing. Another advantage of using this algorithm in UV disinfecting robot is, it will achieve the maximum path with accuracy and effective germ clearance.

2.2. UV bot components used

Raspberry Pi 4 + is the most advanced Wi-Fi compatible micro-controller used for controlling any type of Wi-Fi-based IoT device or application as depicted in Fig. 2. The hardware used in the project is 8 GB ram with an extensive memory card of 16 GB. The microcontroller has two USB 2.0 and two USB 3.0 ports. The board supports micro HDMI and can be powered using USB – C type charging port. The mode of coding the microcontroller is Python and the same is used to develop the algorithm on path planning. The Pi supports a 4 K high-resolution display and can be interfaced with a keyboard mouse and pen drive similar to a computer. The raspberry pi camera comes with the active %MP resolution and a flexible cable for easy connection and access. The camera can be accessed to the Raspbian software or via python coding. This camera is widely used in Face detection and drone-based projects. It's a 3.3 V tolerant robot and does not require much effort on connecting the camera with the microcontroller. The port in the microcontroller fits the camera cable, but much attention is needed on the fixing part as it may physically damage the camera port or the cable. The mismatch or removing the camera during the operation may result in permanent burn or damage to the camera sensor's voltage as it is very sensitive to voltage. In this project, humans cannot enter the disinfection area thus the live streaming of the area is done using this camera. PIR sensor is used in motion detection with the use of Hall Effect sensors. The PIR works on a pyro-

electric sensor that detects different levels of IR radiations. It is mostly used in human detection fields. The sensor receives the IR temperature from the human body and identifies the human motion. This is done by converting this IR signal to an electrical signal. This sensor tolerates 12 V and the sensitivity of the sensor can be modified using the on-board potentiometers. Some of the used components which contribute major part to the robot movement are listed below. Along with the Ultrasonic sensor, relay module. DC motor and Buzzer were used.(See Fig. 3. Fig. 4.).

2.3. UV bot – 3D modelled

The UV – bot was modelled and simulated in a 3D environment for the testing and autonomous navigation demonstration purpose. The robot is designed in reference to a life-sized ratio with 8 LED bulbs and reflectors in between to achieve maximum efficiency. The model is designed with the size and height ratio to achieve optimum accuracy in the disinfection process. The display and charging ports are subjected to modification and is designed only for simulation purpose. The casing around the UV lights are a physical protection to them in case the robot malfunctions. The test area for this robot is modelled with reference to a medical examination centre which includes pathways and obstacles in between. The 3D model of the robot in simulation showed a 3 – 5 % of error in obstacle avoidance and edge detection. As the area resembles a clinic pathway the disinfection rate was also calculated.

3. Results and discussion

3.1. Robot working results

The robot circuit is controlled by Raspberry Pi 4, with sensors to control the robot motion such as Ultrasonic sensor, PIR sensor and a Pi camera for live streaming of the robot operation area. The robot comprises of Motor driver – L298N to control the wheels in the operation area. PIR helps the robot check the human intervention in the work site to avoid any damage to human in UV disinfection process. The ultrasonic works as an obstacle avoidance with a

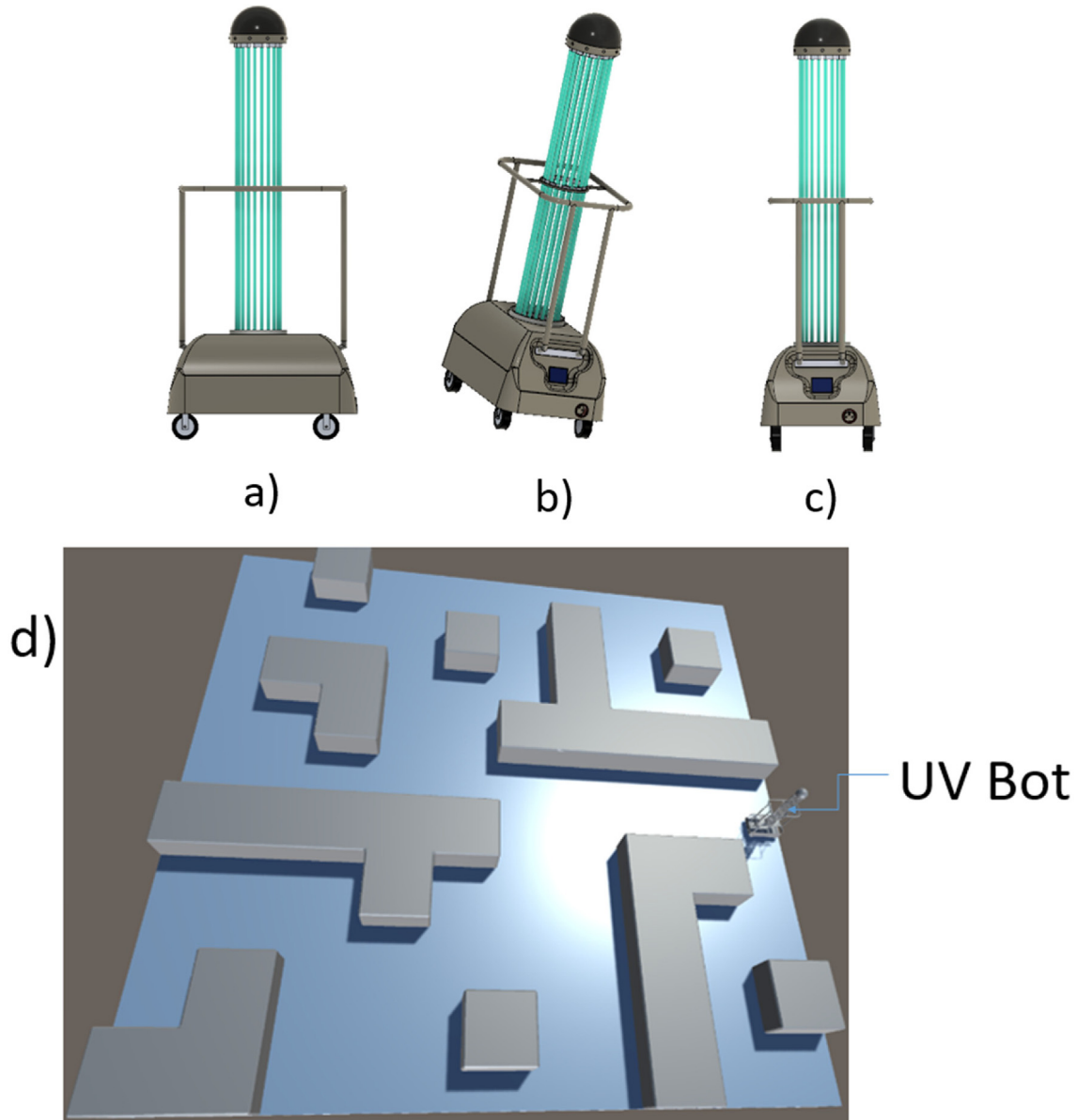


Fig. 3. UV Bot a) LED b) Display and charging port c) UV bot 3D model side view socket d) UV bot 3D modelled Test area – simulation.

buzzer to alert the control room. The relay module is responsible for the human detection and UV disinfection. The robot is powered with Li-Po battery of 3.7 V each in 3 numbers.

Fig. 5 depicts the prototype of the above proposed model implemented with one UV lamp due to the battery constraint initially. The model has an accuracy of 85% disinfection and germ clearance at the same time it takes the optimum time and distance from the disinfection area. As the simulation is carried out for the 3D model and its working, the development of this prototype to life-sized robot will output the accuracy and optimal parameters at the error rate of $\pm 3\%$ which can be further reduced on map modeling and training the robot memory.

3.2. Taguchi analysis

Taguchi analysis is carried out using Minitab v18 software which is commonly used in the field of research to validate or process the obtained information and predict the accuracy or data model. In the UV bot the analysis is carried out to validate that

the robot disinfects a particular area and the percentage of viral clearance is 96.8%. In this case, Germs cleared (%) is the output parameter and “larger is better” function is used as mentioned in Equ.(2), because maximum value of germs cleared is desirable to quickly disinfect the room using Larger the better.

$$S/N \text{ ratio} = -10 \log \left(\frac{1}{n} \sum_{i=1}^n \frac{1}{y^2} \right) \quad (2)$$

Here, n represents number of observed values, y denotes observed data and S/N is the signal to noise ratio.

The disinfection process was carried out on a free room with minimum available obstacles and 25 iterations of data was recorded. The data are the distance covered by the robot over a period of time at a fixed speed which was varied during each iteration. To find the optimum speed and distance at which the robot took minimum time and cleared maximum germs was the objective for the analysis.

L9 Orthogonal array is used and 9 experiments are performed with repetition to obtain the corresponding Germs cleared and

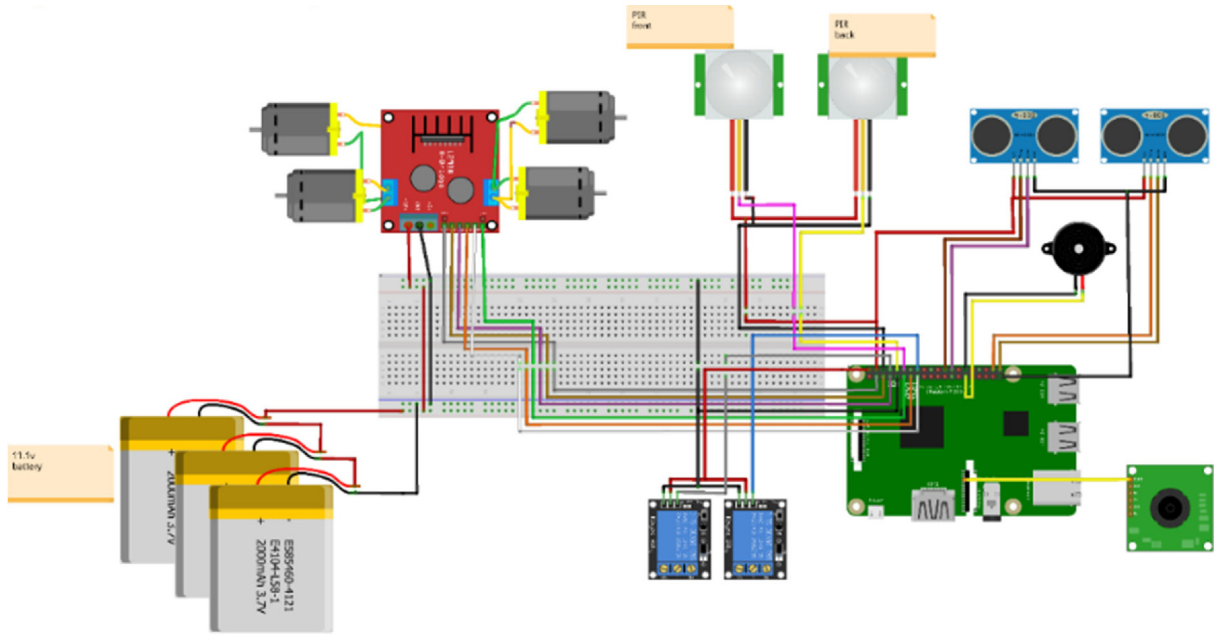


Fig. 4. Circuit arrangement for UV bot actuation.

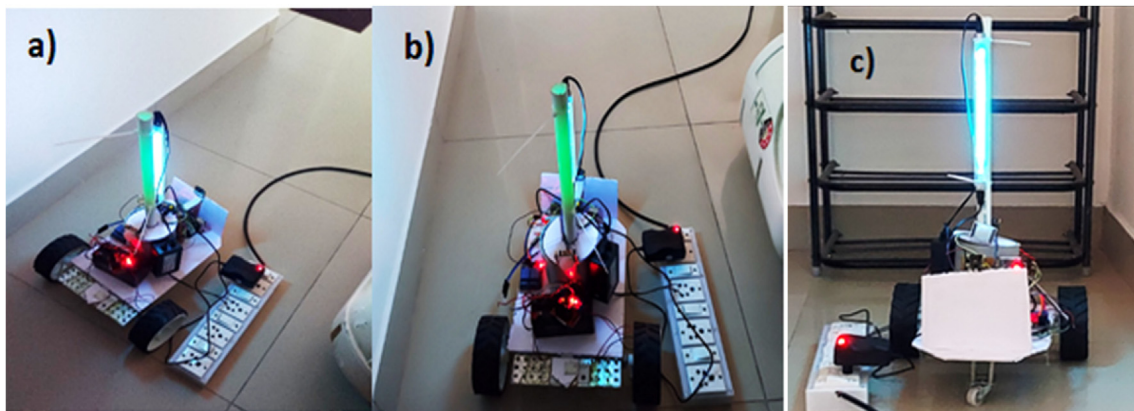


Fig. 5. UV robot model a) side view b) Top view c) Front view.

time of process values. Along with output parameter values, S/N ratios on the basis of germs attained by Taguchi method are shown in Table.1.

Fig. 6 depicted the main effect plots for time and UV Disinfection cleared and S/N ratios obtained from Taguchi method. Since “Larger is better” function is employed in this experiment, peak point levels for each variable are the optimum values for obtaining maximum value of output parameter. Thus, it is implied that optimum combination of variables for obtaining for UV germs cleared is A3B3, where A3 = 0.7 m distance, B3 = 0.15 m/s speed of the robot will cleared maximum % of germs in the room.

As depicted in Fig. 7, the residual plots were plotted to check assumptions of normality, constant variance, randomness, and the presence of outliers. It was found that the normal distribution was followed for time and germs cleared. Predicted value and experimental Taguchi value difference is called residuals. Significance of normal probability plot is to analyze the data collected from UV Robot performance over a straight line. The perpendicular difference between data points and straight line is called error and

sum of the all the error should reflect less than 5 % of data. Both positive and negative side distribution of data is uniformly over the experiments are determined by residual fit.

3D surface plots are generated as depicted in Fig. 8 based on germs cleared by the robot and time taken to complete the robot task. It can be observed from the plot that if the speed of the robot

Table 1
Taguchi Experimental analysis.

Distance(m)	Speed (m/s)	Germs Cleared (%)	Time (s)
0.3	0.05	35.8	28
0.3	0.10	40.6	27
0.3	0.15	55.8	22
0.6	0.05	60.4	30
0.6	0.10	72.8	26
0.7	0.15	85.8	24
0.7	0.05	83.6	32
0.9	0.10	80.2	27
0.9	0.15	79.4	26

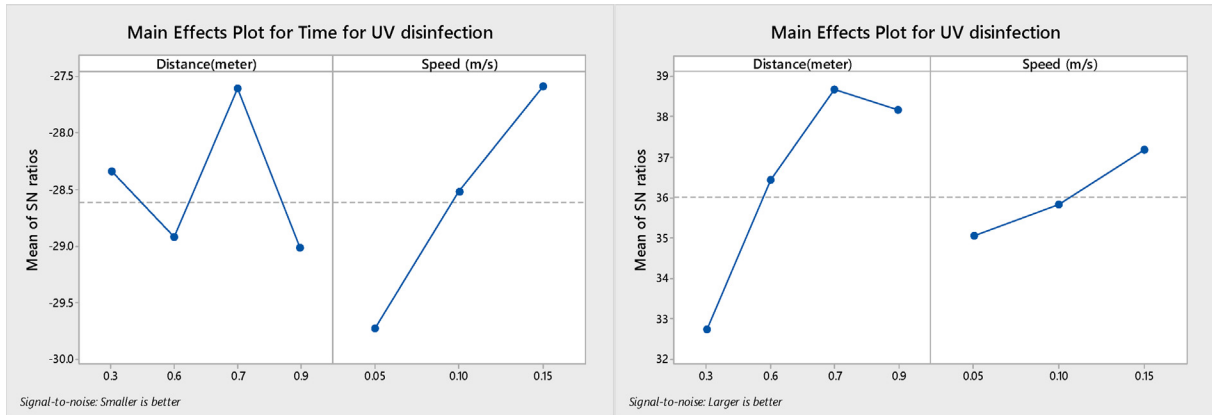


Fig. 6. Main effect plot for time and UV disinfection.

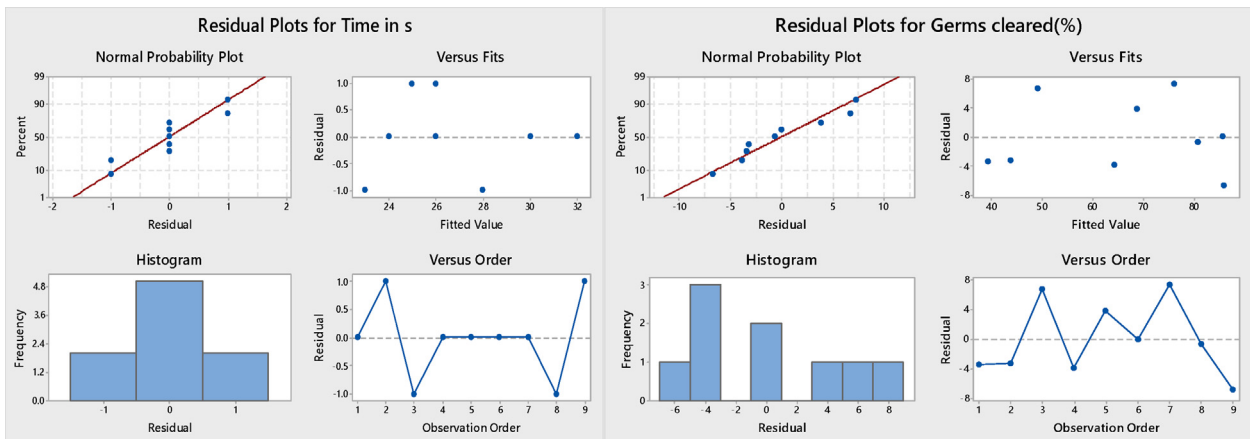


Fig. 7. Residual plot for time(s) left and Germs cleared (%) right.

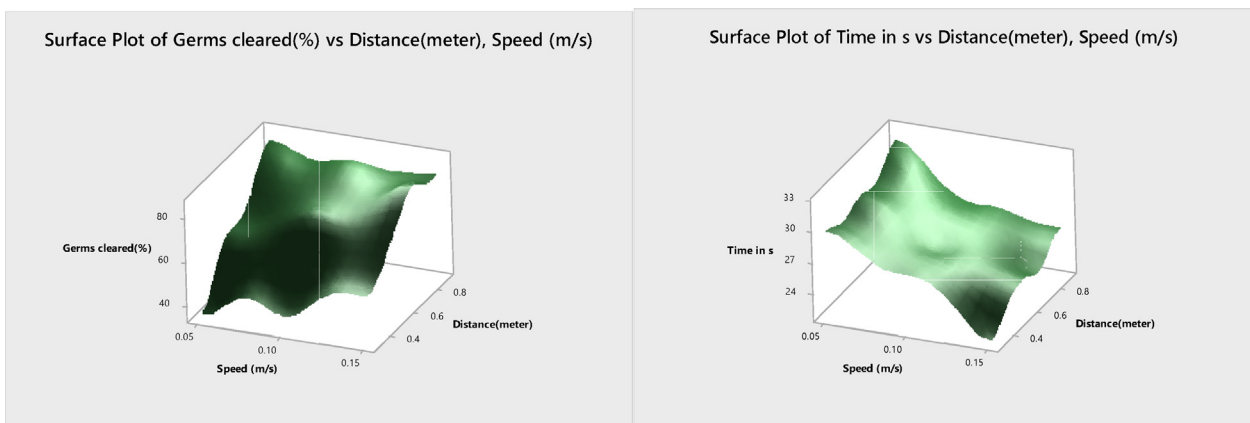


Fig. 8. Surface plot for Germs Cleared and Time taken of the Robot.

is less and with short distance movement the percentage of germs cleared is low and if the speed of the robot is optimum of 0.10 m/sec and optimum distance of 0.5 m the maximum germs was cleared and time taken to complete the task also optimum of 25 sec. With very high speed of the robot with shorter distance of coverage the less germs only identified and cleaned.

3.3. ANOVA analysis

ANOVA stands for Analysis of Variance, which helps in interpreting the data and finding out the influence of variables on output process parameters. ANOVA results for the effect of variables on germs cleared are shown in Table 2.

Table 2
Significant process parameters in ANOVA.

Source	DF	Adj. SS	Adj. MS	F-Value	P-Value	% Contribution
Distance(m)	3	2331.5	777	11.83	0.036*	82.6
Speed(m/s)	2	407.7	53.5	0.82	0.520	14.5
Error	3	107.1	65.5			2.9
Total	8	2845.3				

R^2 -Squ. = 93.01 %, R^2 (adj.) = 81.37 %.

* Significant.

Table 3
Optimized Germs Cleared using Taguchi and Regression analysis.

Levels	Taguchi Optimization Method	Error after Taguchi optimization		Regression Analysis Error after Regression analysis optimization	
		Predicted	Error (%)	Predicted	Error (%)
Germs Cleared (%)	Experimental				
A3B3 (Optimum)	85.8	83	3.26 %	77.47	10.70 %

This analysis is conducted at 95 % Confidence interval and most influencing parameter is found out by most contribution of the parameter. It is inferred that, distance of the germs with robot is the most influencing factor to detect the infection as it contributes 82.6 % than speed of the robot contribute very less of 14.5 %. The error occurs on this data is less than 5 % is acceptable and less p value of 0.036 is the most significant parameter with large F value of 11.83. Large f value indicates that better model fit the data very well using this ANOVA analysis.

The prototype developed with the above mentioned components disinfects a 12*12 room size, 24 Seconds and a speed of the robot is 10 m/s with a distance of identification of germs is 0.7 m from the wall and the germs in the surface is killed with an accuracy of 95.60 % under room temperature.

3.4. Regression analysis

Regression analysis is a statistical method to identify the relationship between the response variable (dependent variable) and

multiple continuous or discontinuous factors (independent variables). In this paper, multiple regression analysis is done to establish a relation between Germs cleaned (%) and the factors over which it depends. The independent variables were the speed of the robot and distance travelled by robot. The mathematical equation obtained by multiple linear regression is shown in Eqn.(3–4).

$$\text{Germscleared} = 15.79 + 63.2 * D + 116.3 * S \quad (3)$$

$$\text{Time} = 31.85 + 3.33 * D - 67.78 * S \quad (4)$$

Optimum results were obtained using Taguchi Optimization Method for the Germs cleared values and ANOVA analysis is performed to determine the contribution of individual factors over the response. Verification tests were performed to test the accuracy of the optimized results. The tests for the Taguchi method were performed by calculating the S/N ratio of optimized level (η) and the germs cleared value (Gc) from Equ.(3) and (4). The

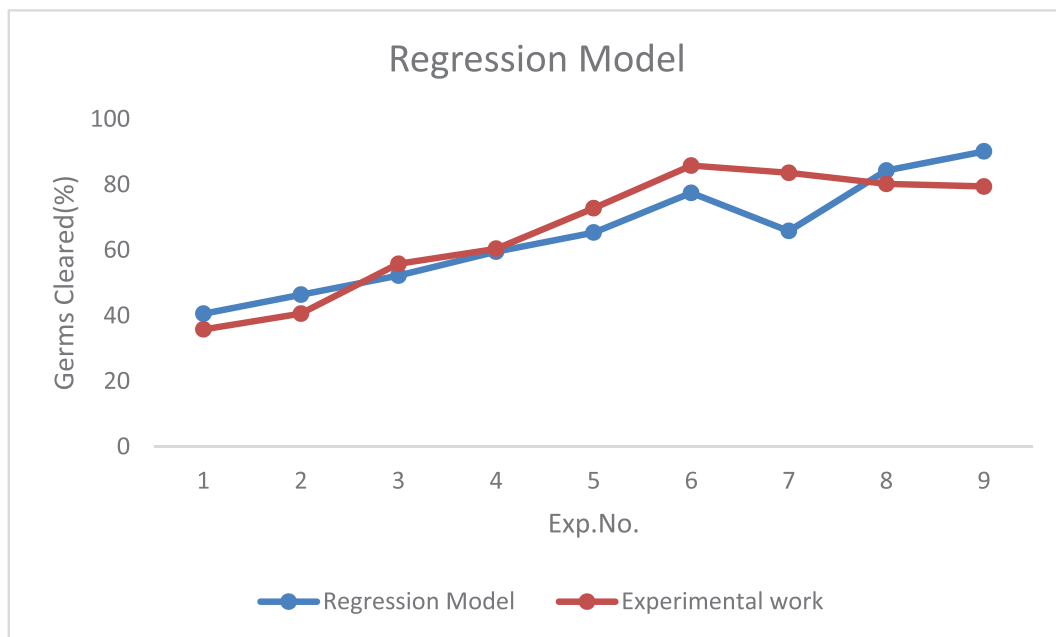


Fig. 9. Comparison of Predicted vs Experimental work model.

estimated germs cleared (Gc) value is based on the optimum combination of A3B3 (A3 = 0.7 m distance, B3 = 1.5 m/sec speed of robot).

$$\eta_{gc} = \eta_{\bar{N}} + (A_3 - \eta_{\bar{N}}) + (B_3 - \eta_{\bar{N}}) \quad (5)$$

In the equations, A3 and B3, and the signal to noise ratios for the optimum level of factor (A3 = 0.7 m distance, B3 = 1.5 m/sec speed of robot) obtained from the Fig. 5. $\eta_{\bar{N}}$ is the average of S/N ratio of all the 9 values. The estimated value of Germs cleared Gc using equ.3 is calculated to be 83 %. Confidence interval (CI) is used to compare the predicted value with the experimental tests.

The comparison between the predicted values obtained through Taguchi Method and experimental results is shown below.

Table 3 presents the comparison of experimental data with the Taguchi optimization and regression analysis. Since the error is very minimal (3.26 %) and is within the permissible limit (less than 20 %) as approved by ICMR [15], the developed UV bot could be used for the sanitation of public places.

4. Confirmation tests

The Fig. 9 represented the germs cleared obtained from experimental, Taguchi analysis and Regression analysis. The accuracy of Taguchi predicted and real experimental values are less than 5 % error.

5. Conclusion

Every medical innovation is brought up for the betterment of patient lives. To this day, there exist procedures for disinfecting the premises. This can be a better alternative to existing disinfection methods which are tedious and time consuming but less effective. Treating a particular area with UV radiation ensures maximum safety and high germ clearance at the point. Not only restricted to hospitals but to offices, malls, theatres and other public places after working hours can make use of these kind of robots to ensure better safe environment.[7,8,9–17]

1. The robot is developed to operate autonomous and self-driven with human detection and obstacle detection thus can be trusted unmanned in any area. Also the obstacle avoiding criteria is more supportive in case of sensitive devices or areas. This bot covers the maximum portion of the room allotted thus achieve higher efficiency.
2. Alongside the robot covers both room surface and floor thus appears more effective in operation. Though any machine cannot achieve 100 % efficiency this robot tries to cover the maximum areas possible to provide a safe environment to the users.
3. The experimental results obtained from Taguchi Method and ANOVA strongly agree with each other and both the results show that most influencing parameter in calculating Germs cleared (Gc) is distance of the robot with contribution of 82.6 %.
4. Taguchi Optimization Method shows that the optimum parameters for Germs cleared (Gc) are obtained at the combination A3B3 i.e. the maximum Germs cleared (Gc) is observed by the optimum distance with optimum speed (A3 = 0.7 m distance, B3 = 1.5 m/sec speed of robot).

5. The results obtained from Taguchi optimization method and Regression analysis are validated using verification tests and the obtained values are within the confidence interval with an error percentage of 3.26 % and 10.7 % for optimum combination.

CRedit authorship contribution statement

Vigneswari Gowri: . **Prabhu Sethuramalingam:** Validation. **M. Uma:** Software, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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