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Design and performance of solar-powered surveillance robot for agriculture application

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Abstract
Agriculture can benefit from robotics technology to overcome the drawback of limited human labor working in this sector. One of the robot applications in agriculture is a surveillance robot to monitor the condition. This paper describes a surveillance robot that is powered by a capacitor bank charged by a mini solar panel. The solar-powered robot is well-suited for deployment in open agricultural areas in Indonesia, where the irradiance is high. This potential is excellent for generating electricity and charging electric vehicles, such as those used in agriculture. The surveillance robot developed and tested in this study has been successfully deployed in an agriculture-like setting with all-terrain contours and the capacity to avoid obstacles. During high irradiance sunny weather, the shortest charging time was 2 hours. Hence, the proposed technology is effective for designing a surveillance robot for agricultural applications.

1. Introduction

Indonesia's renewable energy development promises numerous applications in various industrial sectors and everyday life. People can reduce their reliance on government-supplied electricity by using renewable energy [1][2]. Solar energy is a type of renewable energy that is always available in Indonesia with sufficient levels of irradiation intensity for various applications [3][4]. Solar energy in agriculture, also known as agrivoltaic, can take many forms, including as a source of electricity for irrigation and watering and agricultural robots. The use of solar energy and robots in agriculture have the same objective: to increase productivity and yields while reducing farmer workload [5]-[7], such as solar-powered pumps implemented for automatic sprinkler systems [5], irrigation systems [6], and irrigation system for paddy field in Tanjung Raja villages, South Sumatra [7].

Solar energy can be implemented in any aspect of life, including robotics [8], and both technologies can benefit each other. Robots deployed in agriculture are, in principle, the same as robots used in other fields; the only difference is the types of sensors and actuators installed, as well as the design of the robot [9], which is tailored to the needs of the application during the seeding [10][11], plant maintenance [12], harvest [13]-[24], and post-harvest stages [25]-[27], such as seed-sowing robots proposed by Azmi et al. in 2021 [10] and Kumar et al., in 2021 [11] who were designing and fabricate intelligent seed sowing robot, Hejazipoor et al., in 2021 presents an intelligent spraying robot based on plant condition. The most designed robots are the harvesting robot where image processing for fruit detection, such as Dewi et al. 2021 presented the concept of tomato harvesting [13], van Herck et al. 2020 proposed the sweet pepper harvesting robot [19], and Pereira et al. in 2018 predicted the ripening papaya based on the digital imaging and random forest [24]. The post-harvest stage robots were proposed by Dewi et al. in 2021 and proposed the concept of two robot collaborations for automatic fruit packaging systems [25] and Dewi et al. in 2021 to sort fruit based on color and size [26].

Suppose robots have handled seed sowing, plant maintenance, harvesting, and post-harvesting needs. In that case, there is one more critical area for implementing robots: agricultural monitoring or surveillance robots. Surveillance robots can work 24 hours a day, seven days a week, as an extension of a farmer's eyes to monitor agricultural land. It is hoped that surveillance robots will assist farmers in detecting pests such as monkeys and wild boars, as well as thieves entering agricultural land. Surveillance robots must be able to run smoothly on muddy and rocky terrain. Therefore, the surveillance robot has to be an all-terrain mobile robot with four-wheel drive. This type of 4WD robot undoubtedly requires more power than robots implemented in smooth fields, such as mobile robots implemented indoors. The demand for this robot allows for the development of smart agriculture through precision farming. The robot will work fine if it is equipped with the appropriate sensors. As a result, the proper design will determine the robot's performance. A surveillance robot was employed by Dewi et al. in 2019 as a pilot project for a pipe-inspecting mobile robot [28], which is not a 4WD mobile robot, and an android-based mobile robot was presented by Azeta et al. in 2019 [29].

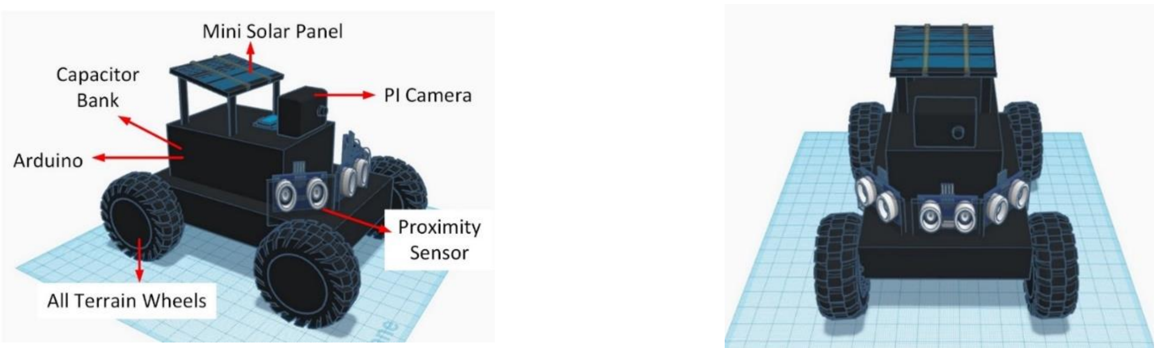
Robots employed on agricultural land in Indonesia will be more economical if they use solar power as their primary source of electricity, given that open agricultural land in Indonesia is subjected to continuous high-intensity sun irradiation throughout the year. Of course, this great intensity of irradiation can be used to charge solar-powered robots [30], as presented by Septiarini et al. in 2022 by designing a solar-powered mobile manipulator whose motion is controlled by a fuzzy logic controller.

Instead of using batteries with its limitation, the capacitor bank is more beneficial to power the electronic components of the solar-powered robot. The advantages of capacitor banks are large peak current, low inductance, high di/dt rating, superior reliability, long life duration, and improved fault tolerance capabilities, which are essential for a storage system [31]. The surveillance robot can be charged during the day and take the energy from the capacitor bank during the night.

This paper presents the design and performance of a solar-powered mobile robot implemented as a surveillance robot in an agrivoltaic application. The 4WD all-terrain mobile robot is set to monitor the condition around the field or is considered an agrivoltaic environment, which is powered by a capacitor bank charged by a mini solar panel. The effectiveness of the proposed method was proven by deploying the prototype of a solar-powered surveillance robot in 7 days in charging and moving in all terrain contour agriculture land. This robot is expected to operate during all weather conditions and the night. The surveillance robot has a wide range of applications, from abnormality detection of plants to security robots.

2. Research Method

The robot considered in this study is the 4WD mobile robot that is required to be deployed in agriculture. The robot is expected to run in an all-terrain vehicle. The studied robot has a wide range of applications, from seeding robots to spraying robots. The novelty of this robot is that it is powered by solar cells and has the ability to move with and without direct charging. The robot mechanic design is shown in Figure 1, equipped with a proximity sensors and PI camera. A capacitor bank is implemented here as the substitute for a battery charged by a mini solar panel. 4 motors move the 4WD all-terrain wheels to support mobility. Figure 1a is the side view of the considered robot, and Figure 1b is the front view. Figure 2 shows the one-line diagram of the surveillance robot in Figure 1. Three proximity sensors are crucial to ensure a crash-free, and Pi Camera enables the user to monitor the environment around the robot.



(a) Side view

(b) Front view

Figure 1. 3D design of the surveillance robots considered in this study

The mini solar panel is the main power source to charge the capacitor bank. Charging is possible when operating and during idle time. The robot can take power directly from solar panels and capacitor banks. The charging time is highly dependent on whether the condition leads to the amount of irradiation received by a solar panel. Figure 3 shows the complete single-line diagram of the solar-powered robot considered in this study.

The current generated by the mini solar panel installed on the robot that charges the capacitor bank is given by Equation 1.

$$J = J_{ph} - J_0\left(e^{q\left(\frac{V+IR_s}{AkT}\right)} - 1\right) - \frac{V + IR_s}{R_{sh}} \quad (1)$$

where J_{ph} is the current generated as light start to pour on the mini solar panel, J_0 is the initial current ($J_o = qA\frac{Dn_i^2}{LN_D}$), R_{sh} and R_s are the parasitic resistance, and V is voltage. The generated current flows due to potential differences or voltage generated by the mini panel, as follow Equation 2.

$$J = J_{ph} - J_0\left(e^{q\left(\frac{V+IR_s}{AkT}\right)} - 1\right) - \frac{V + IR_s}{R_{sh}} \quad (2)$$

where A is the panel area (cm^2), D is the diffusivity of the minority carrier (cm^{2}s^{-1}), n_i is the intrinsic carrier concentration (cm^{-3}), L is the minority carrier diffusion length (cm), N_D is the doping (cm^{-3}), n is diode ideality factor, k is the Boltzmann constant (1.380649×10^{-23} m^2 kg s^{-1} K^{-1}), T is the absolute temperature (K), q is the electron charge ($1.60217646 \times 10^{-19}$C), and J_{sc} is the short-circuit current (Am^{-2}).

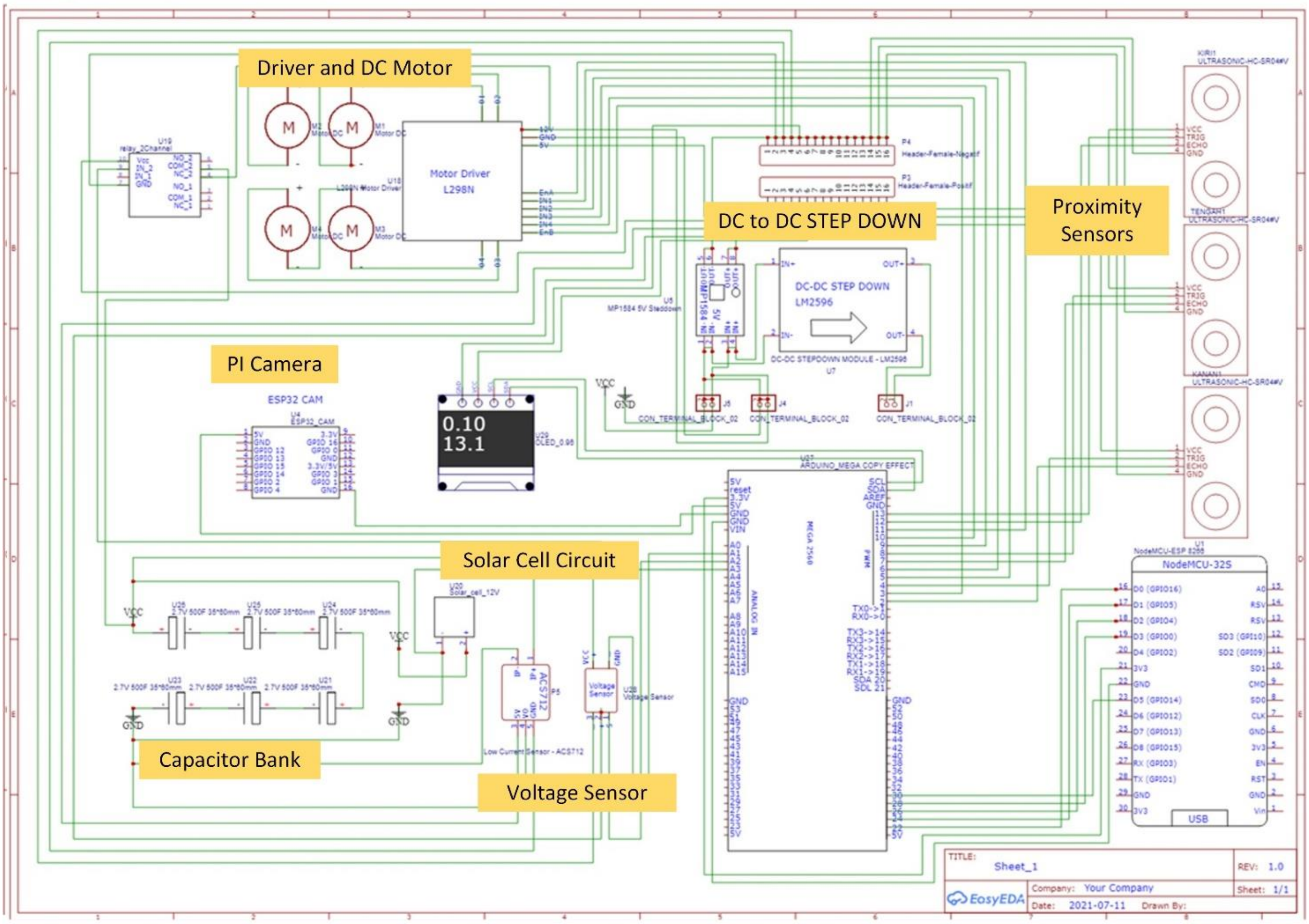


Figure 2. One-line diagrams of the surveillance robots in Figure 1

The main source in this study is a 2,7 V 500F capacitor charged by a polycrystalline silicon solar panel. The capacitor bank has a voltage capacity of 16.2 V; however, the input. Charging the capacitor bank is accomplished by connecting the solar cell cable's output to the capacitor bank's input. The output of the capacitor bank is then connected to the switch as an ON/OFF robot. An OLED display is installed on the robot to indicate how much voltage and current is charged to the robot.

The robot can be deployed in two ways: automatically or manually using a wireless controller. However, obstacle avoidance is performed automatically for both alternatives because of the limited user view from the controller display. Three ultrasonic sonics for automatic obstacle avoidance are placed for this purpose, and Blynk apps handle manual navigation through remote control. If the voltage on the capacitor bank is 7 V, the motor driver will slow down, and if the capacitor bank is not instantly charged, the robot will turn off since the output voltage to turn on the controller system on our robot is 7 V.

Capacitor bank energy storage is modeled as RLC (resistor-inductor-capacitor) circuits. ESR (Equivalent Series Resistance) is the resistive and dielectric losses in the capacitor, and ESL (Equivalent Series Inductance) is the inductance of capacitor lead and current path through the capacitor, as shown in Figure 3. This charging system in Figure 3 is connected to the robot system, as is presented in Figure 2.

ESL losses can be decreased using a dielectric medium with a low-loss factor dielectric film or fluid and employing correct bushes, lead welding, and soldering techniques. However, due to the skin effect, ESR losses increase with frequency. The presence of ESL reduces the di/dt rating of the capacitor. Metal foil with a high width-to-length ratio, extended foil design, radial bushing, and parallel pads can help to reduce this. R_{dc} and R_{ac} are the dc and ac dielectric loss equivalent resistances. Another essential capacitor parameter is dielectric absorption, which occurs when the capacitor's dielectric cannot be quickly polarized. Because of this feature, the capacitor cannot be entirely depleted even after a brief short circuit. Even when fully discharged, the capacitor recovers a small dc voltage at its terminal due to parasitic resistance Rd and capacitance Cd.

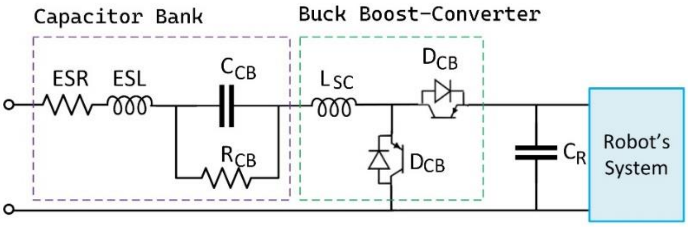


Figure 3. Charging system for the solar-power robot

The capacitor voltage is kept constant during charging (V_{max}) with a series of resistors "R" installed to apply the voltage. During initial charging, the capacitor is charged at a higher rate; however, when it is almost full, the flowing current is considered negligible. The minimum resistance (R_{min}) applied on the capacitor during the maximum current flow across the capacitor (I_{max}) is Equation 3.

$$R_{min} = \frac{V_{max}}{I_{max}} \quad (3)$$

The voltage applied to the capacitor during charging (V_C) exponentially increases during the duration of charging (t), as given by Equation 4.

$$V_C = V\left(1 - e^{-t/RC}\right) \quad (4)$$

and the charged store is Equation 5,

$$Q_C = CV\left(1 - e^{-t/RC}\right) \quad (5)$$

During this period, the amount of energy stored in the capacitor (E_c) is Equation 6.

$$E_c = \frac{1}{2}CV^2 \quad (6)$$

and energy dissipated in the series resistor (E_R) is given by, Equation 7.

$$E_R = \int_0^\infty \frac{V_R^2}{R}dt = \int_0^\infty \frac{\left(Ve^{-t/RC}\right)^2}{R}dt = \frac{1}{2}CV^2 \quad (7)$$

while the energy charged comes from the mini solar panel (E_{SP}) is calculated as Equation 8.

$$E_{SP} = E_c + E_R = CV^2 \quad (8)$$

furthermore, finally, the Efficiency of charging of capacitor (η) in the constant voltage method is Equation 9,

$$\eta = \frac{E_c}{E_{SP}} = \frac{\frac{1}{2}CV^2}{CV^2} = 50\% \quad (9)$$

The experimental test bed in Figure 1 will be deployed for 7 days to show the surveillance robot's ability to move in an all-terrain environment powered by a capacitor bank charged by a solar panel and avoid obstacles during its deployment. The experiment includes charging and discharging the surveillance robot to show how long it takes to charge the capacitor bank fully.

3. Results and Discussion

The prototype of a solar-powered mobile robot is in Figure 1 as the experimental testbed to show the effectiveness of the proposed method. The robot is deployed in an agriculture-like environment with obstacles scattered around the place. Figure 4 shows the video testing the effectiveness of robot motion, which can move in all terrain contour agriculture and the automatic obstacle avoidance during its deployment (Figures 4b, 4c, and 4d). The prototype size is 34 cm long and 18.3 cm wide, with a height of 26.4 with wheels attached.

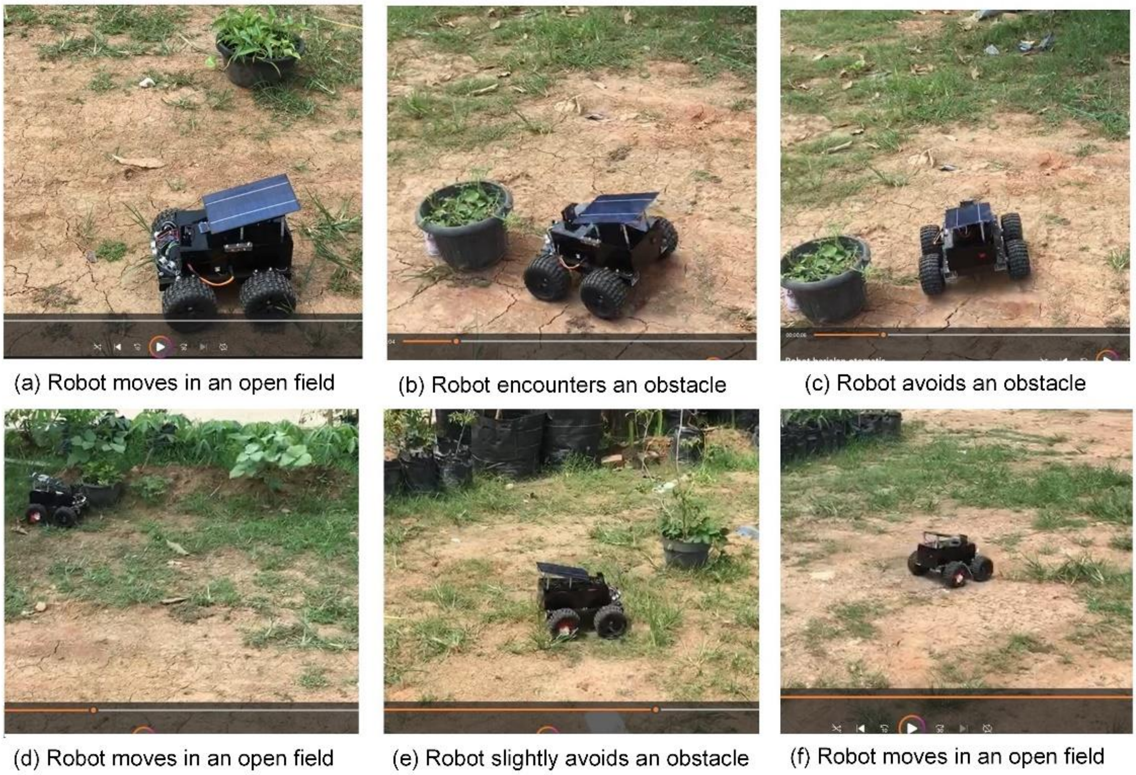


Figure 4. Surveillance robot deployment in an open field

Figure 5 shows the user view through the monitor controller. The limited view while controlling the robot requires automatic obstacle avoidance. This robot can monitor the agricultural environment for safety or repel pests such as monkeys or other large pests. Figures 5b and 5e show that as the robot approaches the obstacle, it will automatically avoid it, as shown in Figures 5c and 5f.

The surveillance robot is charged by a mini solar panel installed on the robot. The experiment for charging the solar-powered surveillance robot was conducted for 7 days. The duration from empty to full charge was highly dependent on weather conditions since weather conditions affect the irradiance received by the mini solar panel. The irradiance for 7 days during the experiment is shown in Figure 6, where the irradiance data was only recorded during charging. The charging time started at 10:00 AM since, in Indonesia, the irradiance peak is from 10:00 AM to 14:00 PM. The highest irradiance was on 28 June; hence the fastest duration of charging time was 28 June, where it takes only 2 hours to fully charge (10:00 AM to 12:00 PM).

The irradiance on 28 June was not very high, but it was constantly high enough to charge the capacitor bank. On the other days, the weather was changing during the day; therefore, the irradiance fluctuated, leading to a longer charging time to get fully charged. The longest charging time was 25 June, when it took 4 hours to be fully charged, as presented in Figure 7. Figure 7, related to Figure 6, illustrates how much time is needed to charge the capacitor bank due to the fluctuation of solar irradiance received by a mini solar panel.

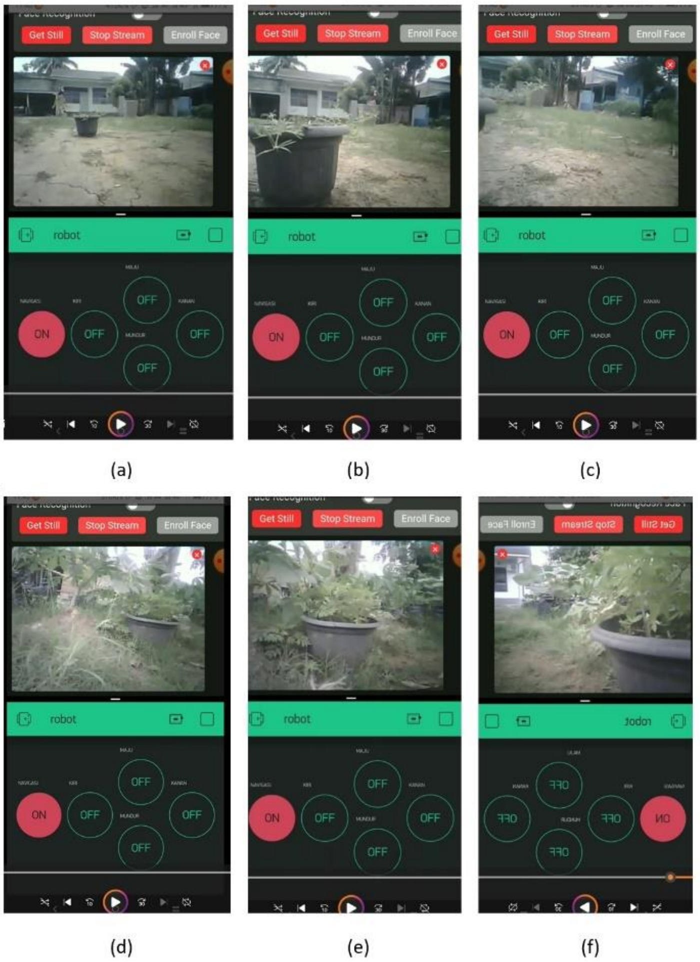


Figure 5. Camera and user view during robot's deployment

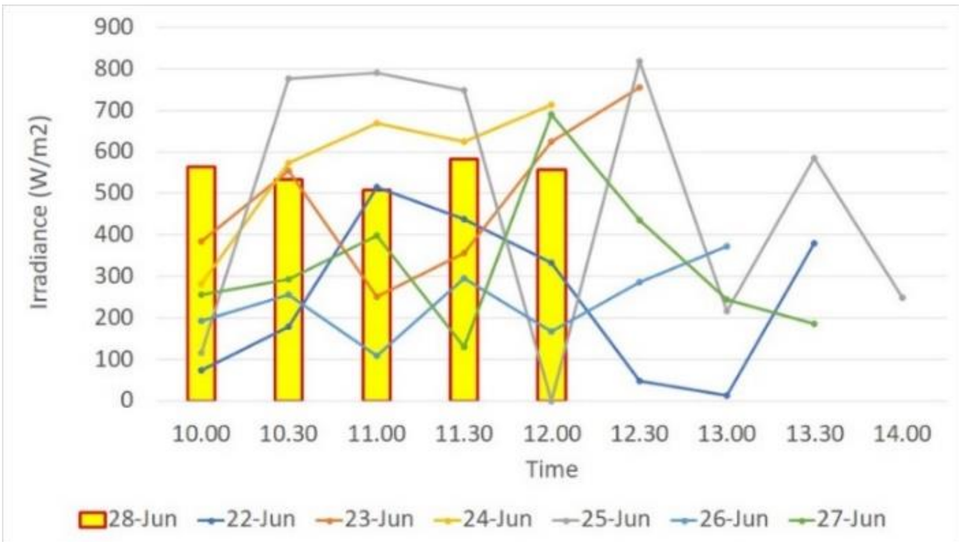


Figure 6. Solar irradiance received by mini solar panel for 7 days experiment

Figure 7. Charging time during 7 days of the experiment

Figure 6 and Figure 7 show that the fastest charging time was on 28 June, and Table 1 presents the weather condition, which was sunny during the 2 hours of charging time. The surface temperature of the mini solar panel was higher than the normal ambient temperature. The voltage and current generated by solar panels were at the highest at 11:00 PM, 13 V, and 6.54 mA, respectively, due to the high irradiance received by solar panels (669.8 W/m^2). The charging voltage and current to the capacitor bank are the highest at 12:00 PM, and the highest current charged to the capacitor bank is 5.32 mA.

Table 1. Experimental test during charging

Time	Weather	Irradiance (W/m^2)	Surface Panel Temp (ºC)	V_{SP} (V)	I_{SP}(mA)	V_C(V)	I_C (mA)
10.00	Sunny	282.3	36.1	10.13	4.18	8.78	3.26
10.30	Sunny	574.3	45.7	11.58	7.12	11.12	3.99
11.00	Sunny	669.8	53.2	13.00	6.54	12.43	4.17
11.30	Sunny	624.5	53.0	12.79	4.74	13.02	5.32
12.00	Sunny	713.0	53.2	12.97	4.24	13.20	4.42

The surveillance robot demonstrated in this research has automatically avoided obstacles and moved smoothly on the all-terrain field that will be experienced if deployed to agricultural land. Agricultural land is often located in open areas with high irradiance intensity, and this potential is excellent if used to charge agricultural robot batteries. This notion is supported by the fast-charging time when the irradiation is high enough. As a result, solar-powered robots are well-suited for use on agricultural land in Indonesia in general and in South Sumatra in particular.

4. Conclusion

This paper describes a surveillance robot powered by a capacitor bank charged by a small solar panel. The solar-powered robot is well-suited for deployment in open agricultural areas in Indonesia, where the irradiance is high. This potential is excellent for generating electricity and charging electric vehicles, such as those used in agriculture. The surveillance robot developed and tested in this work has been successfully deployed in an agriculture-like setting with all-terrain contours and the capacity to avoid obstacles. The experimental result shows that it is more effective to have a solar-powered mobile robot for agriculture due to its deployment in the open field with high-intensity solar irradiance. The proposed robot is an all-terrain vehicle that can move easily in all contour environments. During high irradiance sunny weather, the shortest charging time was 2 hours. As a result, the proposed technology helps produce a surveillance robot for agricultural applications.

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