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Designing and implementing a multi-function board to increase the operation time of mobile robots using solar panels

Ali Jebelli[1], Arezoo Mahabadi[2]
[1]Department of Mechanical Engineering, University of Alberta, Edmonton, Canada
[2]Department of Basic Engineering Science, Tehran University, Tehran, Iran

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ABSTRACT

Today, the use of mobile robots and autonomous vehicles has increased due to their use in various industries, and their performance and duration of operation largely depend on the amount of energy consumed and their batteries. One of the ways to increase the operation time of robots is the use of solar panels that can charge their batteries while moving, but the amount of energy received from solar panels reduces their efficiency due to factors affecting them, such as the angle of the sun, weather conditions, and their use in mobile robots alone is not recommended. In this research, we introduce an electric circuit with very low losses to increase the received power of solar panels and increase their efficiency, which is able to supply the power of the robot through solar panels when the sunlight and the angle of radiation are suitable and charge the batteries through the maximum power point controller (MPPC), and by reducing the amount of energy received from the panels by changing the energy source to the battery, the duration of the system's dependence on the battery has decreased, which increases the duration of the mobile robots.

Corresponding Author:

Ali Jebelli
Department of Mechanical Engineering, University of Alberta
Edmonton, Alberta, Canada
Email: ali.jebelli@ieee.org

1. INTRODUCTION

Currently, the high consumption of fossil fuels such as oil and gas meets a large share of the need for fuel all around the world; regarding that, the mentioned fuels will run out, and many countries have admitted renewable energy as a proper substitution for fossil one. Solar energy, which is available in abundance and unlimitedly, has been considered one of the most important renewable energy sources. It should be mentioned that, in new systems within which it is not easy to access fossil fuels, renewables such as solar energy can be used in some cases, such as mobile robots [1]–[4]. For example, using renewable energy in space systems is inevitable. The current satellites in space use solar energy to fulfill the need for energy [5]. Despite the numerous advantages of renewable energies, instability, and unusability in all conditions have not allowed such fuels to reach their real place in human life. For example, dust and dirt on solar panels can reduce the panel power output by 15% per day [6]; therefore, the efficiency of such resources will be decreased gradually. Furthermore, depending on the environmental conditions, such as the change of seasons and day and night, the reliability of this type of energy varies; in the first six months of the year, in countries where the intensity of sunlight is sufficient, this energy is generally significant, and in the second six months of the year, depending on the different weather conditions, the reliance on these systems decreases. A multitude of research has been carried out to increase the efficiency and effectiveness of these systems. Considering the mentioned problems, many people have looked forward to solving the problem within their system. Popovski and Ackovska [7] sought to build a deformable modular robot to control weight at any phase of testing and construction and be modified and upgraded easily in order to be capable of supplying energy to the robot by using a renewable source; In addition, it has been tried to minimize the dependency on human operators to implement some projects. In addition, finding a suitable driver according to the characteristics of the robot is one of the things that has been considered in this research.

Park *et al.* [8] sought to model a beam based solar robot to operate with solar cells; the purpose of this research is to minimize the change of direction and sudden deviation along with the vibration of the robot, and the results obtained in this project were favorable both in simulation and implementation [8]. Cammarata [9] sought to build an optimized system that could track the Sun's movement throughout the year; panels were used at angles of o to 50°. Moreover, the system vibration was investigated within the operation; Also, in order to evaluate the performance, the said robot was equipped with fixed panels so that the performance of the system could be measured by both panel models at the same time.

Dust on the surface because of different weather conditions is one of the factors which reduce the efficiency of solar power plants, albeit the problem can be solved by building robots to clean the surfaces. The projects such as Anderson *et al.* [10] looked forward to building mobile robots to clean the panels' surfaces to increase the efficiency of the solar panels. The mentioned robot moved both vertically and horizontally on the panels' surfaces to clean the desired surfaces. Simjee and Chou [11] and Jiang *et al.* [12] used lithium batteries and supercapacitors as substitute resources in their projects. They were looking for a simple, reliable design with minimal human intervention, hence considering the batteries as a power source in their systems; in addition, capacitors can also act as a battery in the system to minimize the pressure from the load on the panels. It should be added that it is not recommended to use batteries as a power supply in isolated environments. Since robots usually operate indoors, it is better to consider batteries as a secondary power supply. On this basis, the solar source can be used as the main source while batteries as the secondary one; therefore, in the system designed in this article, panels with the aid of capacitors have been considered as the main power supply while the batteries as the secondary one. It should be added that by reducing the energy consumption of these systems, their performance can be improved while concentrating on motion maps within projects such as Yamasaki *et al.* systems [13] and Zheng and Reif [14] kinetic energy consumption has been reduced. However, items such as sensors and connection tools of robots that are independent of motion consumption constitute a significant share of circuit consumption; hence reducing the consumption of the internal circuit is of utmost importance, which has also been considered in this research. Battery charging using solar panels has received further attention over the years; panels are capable of charging the capacitors, which can be used as a power supply in the system, in addition to batteries during the day. A system within two projects had been implemented that could keep itself operational for a long time and therefore used rechargeable batteries with an automatic charging mechanism [15], [16]. Panels were charging batteries within Parker's project; meanwhile, capacitors were used as another power supply. It should be mentioned that the input resource is determined based on each voltage. A similar project has been designed in the system of the article.

Wolfs and Li [17] sought to optimize mobile systems to be capable of increasing the system efficiency in low and different sunlight intensities; therefore, they designed circuits to increase the system efficiency in different sunlight intensities. Marco and her team investigated the batteries' consumption at different conditions and speeds; the results showed that panels could only supply control and wireless power [18]. On this basis, providing the energy required by the robot's connection system is one of the applications of solar panels [18].

Panessal *et al.* [19] sought to build systems with the aid of the Internet of Things (IoT) to increase system efficiency by tracking the Sun during the day. It was concluded that temperature significantly affects the generated voltage; moreover, they found that it is possible to improve circuit performance using the IoT. Lister and Salem [20] have also used batteries in the robot as the main power supply; generally, the main power supply in their robot had a constant voltage. Since the different system segments required various voltages, the direct current (DC) voltages were generated such that the output voltage was constant while different segments were operating at different voltages. The results showed that the system efficiency has been different from the system consumption. Mobile robots have also received attention in other applications in recent years. Reddy and Poondla [21] sought to build automotive air robots equipped with solar panels; it should be added that the panels have charged the batteries using the maximum power point tracking (MPPT) method. Panels were embedded within the wings, which was considered a new design to increase the reliability of this energy. Eventually, Ramírez-Díaz *et al.* [22] designed an air robot to receive its required energy from sunlight; they designed a system that could fly nonstop for 48 hours.

The ultimate objective of the article is to build a system to provide the energy needed by the system solar panels with the aid of capacitors with maximum efficiency when sunlight is available meantime batteries are charged by panels and are connected to the output power supply circuit whenever the primary power supply is disconnected. In designing a proper circuit, environmental changes have been tried to have the least impact on system efficiency; that is to say, the efficiency of the battery charger system is still at a desirable figure following the reduction of sunlight. In addition, the system can be used alternately with robots such as the ones that clean the solar panels. The maximum consumption of batteries is another prominent feature of this design; so that by using a boost circuit, the system operation time will be increased and the output current controlled.

2. THE PROPOSED METHOD

Different methods have been developed to obtain MPPT, which have both advantages and disadvantages. The first method which was discussed is the perturb and observe (P&O) algorithm, which is a simple one. It should be mentioned that it is not applied in many cases regarding its low accuracy. The system performance is such that the changes to the left of the MPPT point are greater than zero (dp/dv>0) while they are less than zero to the right side (dp/dv<0); Figure 1 shows the specifications of the method. Changing the panels' output voltage can be brought to the MPPT point within the mentioned algorithm. As shown in Figure 1, increasing (decreasing) the voltage will increase (decrease) the power to the left of the MPPT, while decreasing (increasing) the voltage will decrease (increase) the power to the right side. Generally, whenever the power is increased, perturbation should remain constant to be able to reach the MPPT point. The opposite will occur if the power is decreased [23].

$$\frac{dP_{PV}}{dV_{PV}} = 0 \; At\ MPPT \tag{1}$$

$$\frac{dP_{PV}}{dV_{PV}} > 0 \; Left\ side\ of\ MPPT \tag{2}$$

$$\frac{dP_{PV}}{dV_{PV}} < 0 \; Right\ side\ of\ MPPT \tag{3}$$

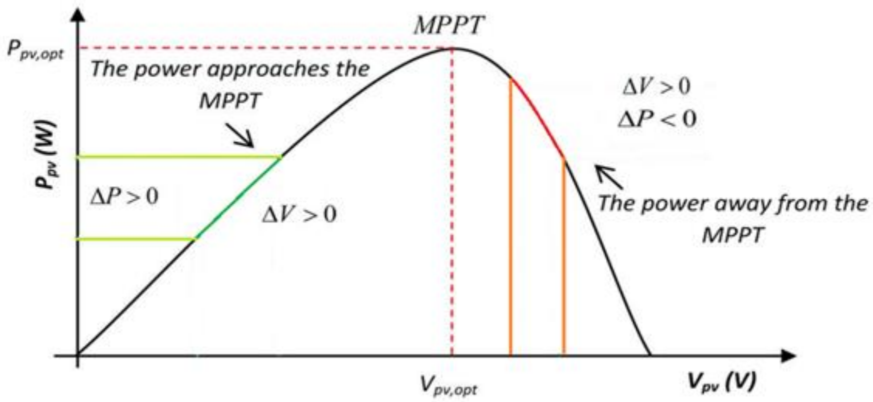

Figure 1. MPPT point range diagram

The system flow chart is shown in Figure 2. High tracking capability, simplicity, and speed of operation are the advantages of this method. In contrast, the fluctuation within the MPPT range makes it impossible to determine the MPPT value in high power losses even in stable conditions [24].

Incremental conductance can be mentioned as another method of determining the MPPT point. The method aims to modify the disadvantages of the previous method. So, the dP/dV used in previous methods has been replaced with the I-V characteristics of the panels. As a result, (4) and (5) are obtained.

$$\frac{dP}{dV_{pv}} = \frac{d(V_{pv}I_{pv})}{dV_{pv}} = I_{pv} + V_{pv}\frac{dI_{pv}}{dV_{pv}} \tag{4}$$

$$\left(\frac{1}{V_{pv}}\right)\frac{dP}{dV_{pv}} = \frac{I_{pv}}{V_{pv}} + \frac{dI_{pv}}{dV_{pv}} = G + dG \tag{5}$$

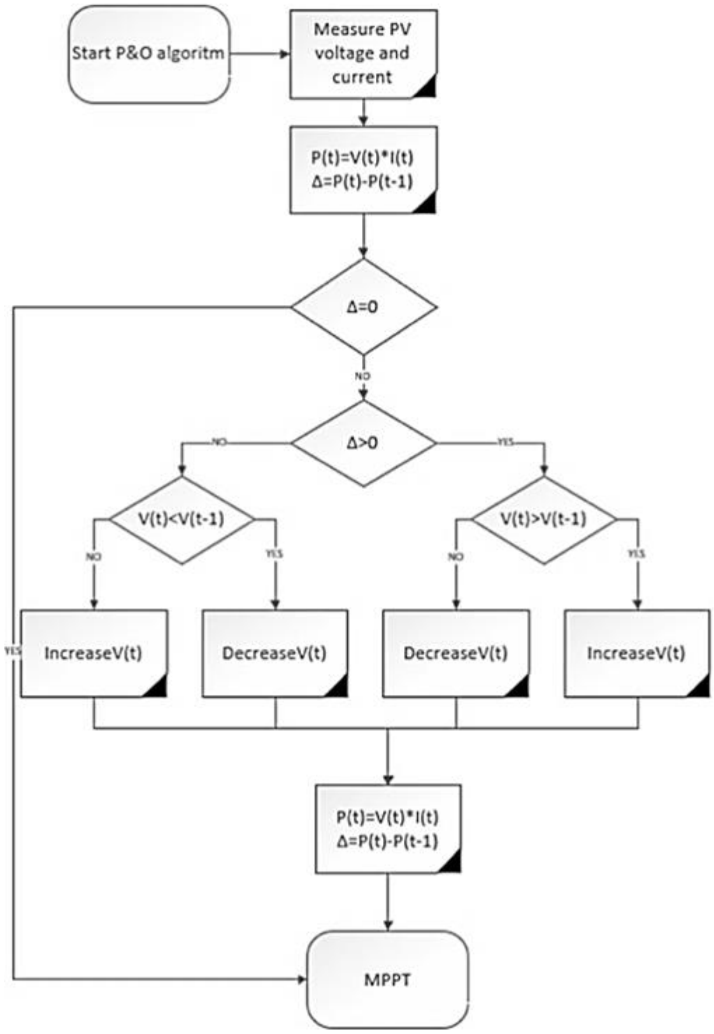

Figure 2. P&O flowchart

G value represents the conductance of the solar panels, and dG value represents its enhancement in solar cells. The method aims to find the difference between the panel performance point and MPPT value. On this basis, the designed output obtains following the difference reaching zero. The flowchart in Figure 3 shows low oscillations within the MPPT range and its main disadvantage, whereas different phases require more expensive and complex controls [24]. Fuzzy control is the next method that is more complex than the previous two but with more acceptable results [25], [26]. Reduced fluctuating noise is the advantage of this method. The most accurate desired point can be reached as soon as possible by neural networks and artificial intelligence (AI). The fuzzy control method includes fuzzy rules, fuzzification, and defuzzification [27]. The controller can reach a high efficiency regardless of whether the information is correct or not [24]. The flowchart is shown in Figure 4. Being needless of the mathematical and scientific model of the solar panel system is the advantage of this method, whereas the complexity of the operator components is its disadvantage [23], [28].

The mentioned methods are a part of the existing techniques to reach the optimal point. MPPT method has been used to have the best performance in a way that whenever the intensity of sunlight is low and the panels' output decrease, the system efficiency increases and fluctuates continuously by being in hysteresis mode. Whenever the intensity of sunlight is low, the regulator, placed at the system's input to create impedance matching, controls the output current by changing the duty cycle. Reducing the duty cycle reduces the output current, and with the reduction of the output current, the input voltage that is supplied through the panels increases, and when the input voltage exceeds a certain limit, the duty cycle increases, thereby increasing the output current; the mentioned cycle is done continuously within a short period of time until either the intensity of sunlight reaches such a low level that the system turns off or returns to an appropriate level. The method can maintain the system efficiency above 80% at low currents (10 mA) [29].

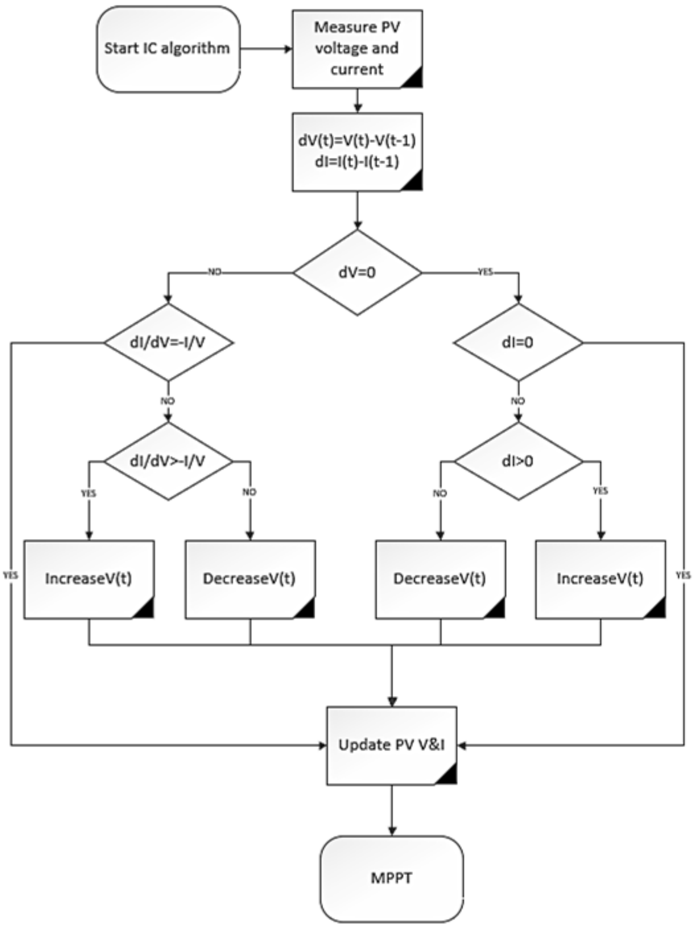

Figure 3. IC flowchart

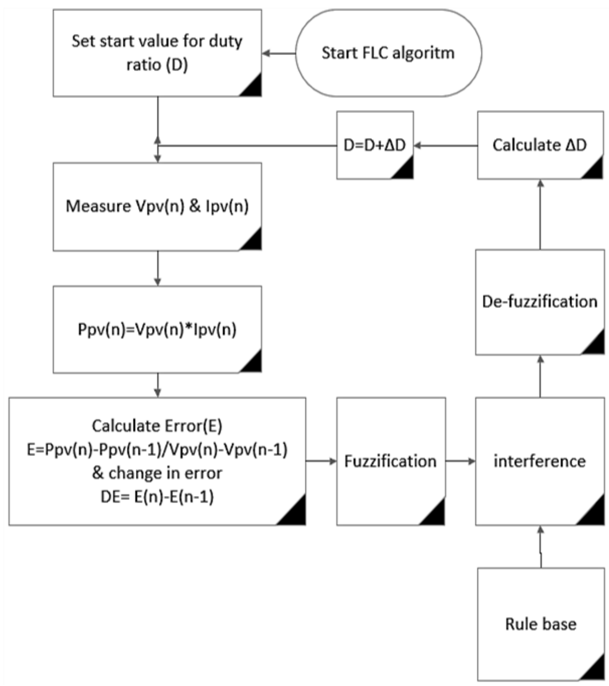

Figure 4. Fuzzy control flowchart

It is necessary to discuss the specifications of the solar panels for simulation. The equivalent circuit of a solar panel is considered to be equivalent to a parallel diode with a current source, provided that the current source is ideal. The output current of the ideal current source is considered proportionate to the irradiated light. Two cases have been considered to be investigated. First, the output is in the form of an open circuit; second, the system is in the form of a short circuit. The circuit output is measured within the two mentioned cases. In many cases, it is necessary to mount two resistors in series and parallel to calculate the power loss. The circuit is shown in Figure 5.

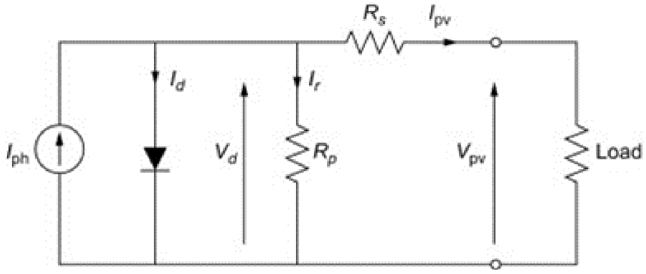

Figure 5. Solar panel equivalent circuit

As shown in Figure 5, I_{ph} output current is proportionate to the irradiated sunlight, which spreads in three directions. One of the currents passes through the diode. The second current passes through the parallel resistor, while the third one is the series resistor [30]. Each solar panel can produce output power to a certain amount; under certain conditions (light intensity and temperature), the power accounts for a certain amount of voltage and current. Ideally, all solar cells have a similar behavior without losses [31]. On this basis, whenever the intensity of sunlight and output power are certain, the output current decreases following the voltage increase and vice versa. The system has been designed by proportioning these two specifications in a way that enters an oscillation cycle and maintains efficiency high within low power mode. As the output current decreases, the input voltage increases; as the output current increases, the input voltage decreases. The output current of solar panels is equivalent to (6) [32].

$$I = I_{Ph} - I_0 \left[\exp\left(\frac{qV+IR_S}{AkT}\right) - 1\right] - \frac{V+IR_S}{R_P} \quad (6)$$

In this article, we have sought to bring the system to the maximum power or MPPT point by changing the impedance of the input circuit, considering that the simplicity of input power can be considered an advantage. The power circuit of this system includes two solar panels and an emergency battery. One of the panels [15], [16] is considered the main power (primary power) to supply the power required by the mobile robots during the day by charging the capacitors. At the same time, the other panel charges the mobile robots' batteries (secondary power) so that in case of interruption of the first power supply (when the intensity of sunlight decreases), the system's energy is supplied through the batteries.

The advantage of this method compared to [15], [16] is that the battery charging circuit, due to its hysteresis property, can maintain its efficiency even in low currents (10 mA) at an optimal level (90%) in low sunlight.

3. SIMULATION AND PERFORMANCE

Considering the mentioned issues in previous sections, simulating the input circuit is discussed in this section, as efficiency is the most important factor of the system; therefore, achieving the highest efficiency and the lowest circuit consumption are the bases of the design. The project aims to supply the system with solar panels during the day. Moreover, lithium batteries that have been considered to supply the circuit are charged by solar panels. Whenever the sunlight is no longer capable of providing the main power, batteries supply the circuit. As the first supply is set, the circuit returns to the first supply. The third power supply (spare batteries) has been designed for the circuit; on this basis, whenever the first and second power supplies are not available within the circuit for any reason (the solar panels do not receive enough light and the batteries do not have a sufficient charge), the third route which is a separate energy source supplies the system; it should be added that, if any of the first or second power supplies return to the circuit, the third power supply will be cut off. To do so, a very simple structure has been used to reduce the consumption of the system.

Figure 6 represents the circuit simulation in LTSpine software. Similar measures have been done in this field; for example, Tokkar *et al.* [33], Wang *et al.* [34], and Kim and Kim [35] had studied the energy consumption in these systems. Eventually, they obtained a complete model for energy consumption within their systems. The results represent the amount of energy loss in each segment of their systems, which led to the system performance improvement.

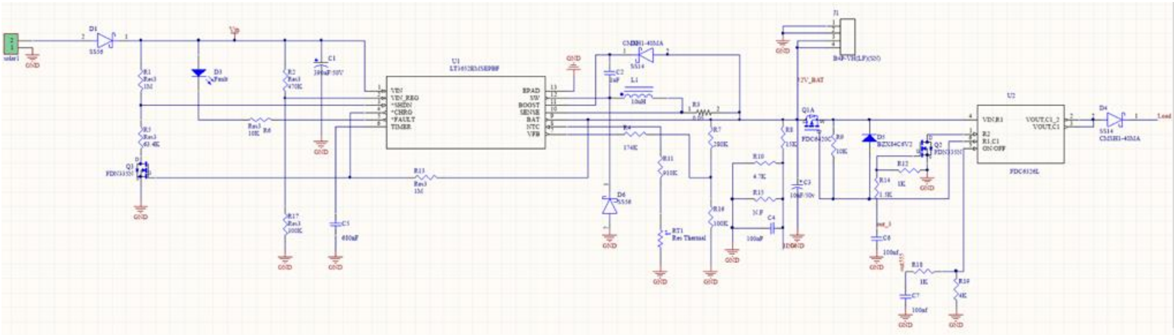

Figure 6. Battery power supply circuit simulation

As shown in Figure 7, whenever the panel voltage is less than the desired range (about 17 V), the output current will decrease. Input voltage increases following the reduction of output currents; it should be added that the mentioned cycle continues permanently till either the intensity of sunlight increases sufficiently or decreases to such an extent that the panel no longer has an output.

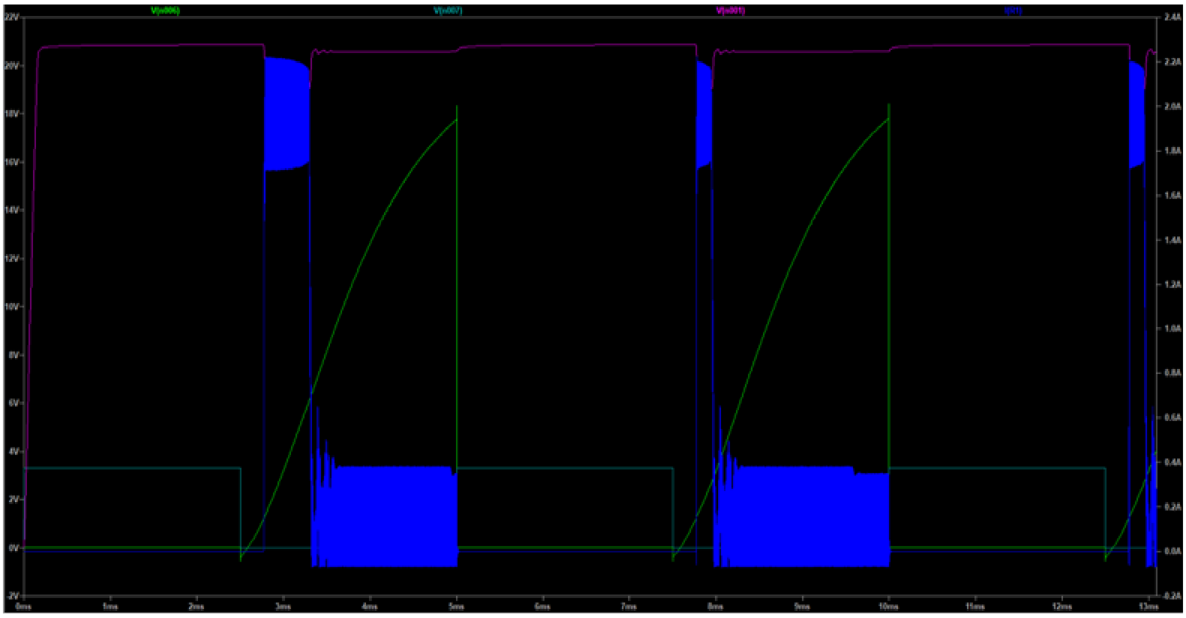

Figure 7. Circuit in MPPC mode, by deactivating the input regulator (green), prevents the reduction of the input voltage (purple)

The circuit shown in Figure 8 has been used to supply the circuit; the method shown in Figure 6 is not practical for the system's main supply since the output current is much above the range (10 mA) and also the current required by the system, which is about 250 mA, makes the system efficiency above 90%. The primary supply circuit (solar panel) is according to Figure 8.

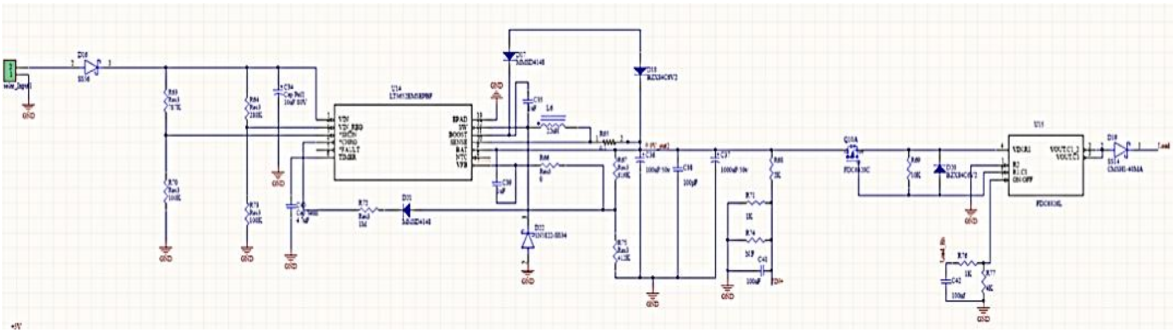

Figure 8. The main power supply circuit of the system

At the output of each circuit, the output of each section is sampled using a voltage divider. When the sampled voltage drops below a certain limit, the power supply circuit of the next section is activated, at the output of each section, due to the fact that the internal diode of the output transistor (U15) causes the voltage to return; it is necessary to design the circuit according to Figure 9, so that the internal diode Q1A prevents the voltage from returning to any power supplies.

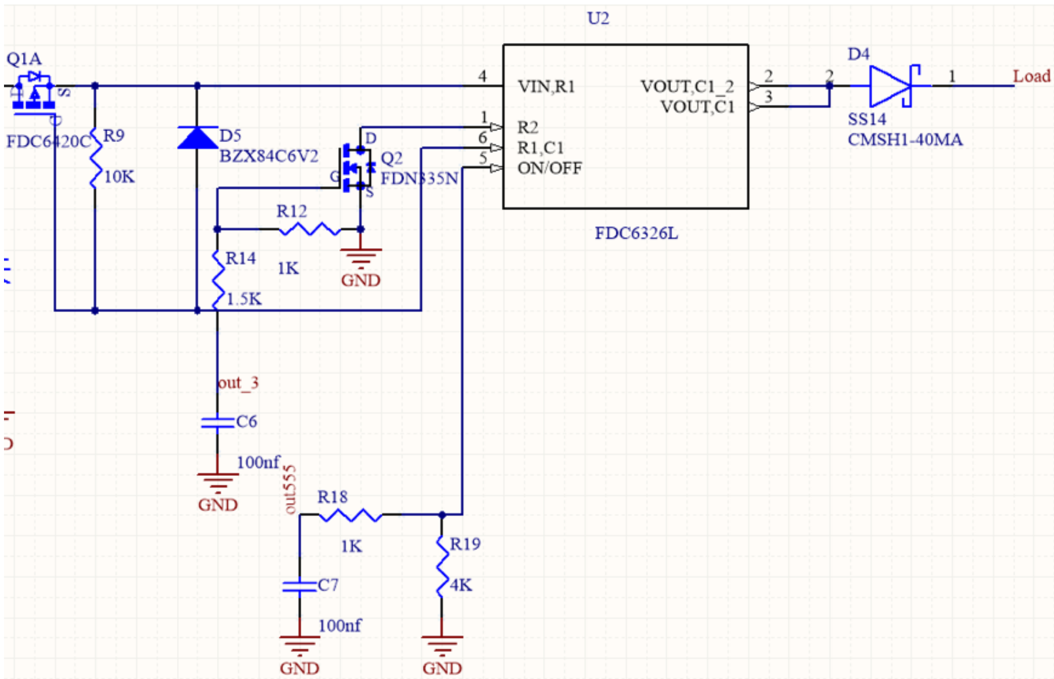

Figure 9. The output circuit of each power supply (according to the direction of internal diode U2, transistor Q1 is placed to prevent voltage from returning)

As shown in Figure 10, when the ON pin is activated in U2, this transistor connects the output of this part to the output of the main circuit; considering that several input power supplies have been used to protect the circuit, it is necessary to use Q1 to prevent the return of the voltage.

Two parts, including LM293D and 74HC14 as shown in Figure 11, have been used to control the system, which is with very low consumption. Whenever the main supply (solar panels) is above the voltage within the comparator circuit, the output of the comparator circuit would be in high mode; it should be added that Node 1A will be in high mode. On this basis, Load-En will be activated then Q10, and U15 output circuits will be activated too. Whenever the output of the comparator circuit is in low mode, Load-En will be in low mode too, and the system output will be deactivated; meanwhile, Bat-En will be in high mode, and also Q1 and U2 will be activated; it should be noted that this is not the only condition for the activation of this system. Robots that are used for certain purposes as in [10], [36] are used only for a part of a day;

therefore, the system is not needed to be operating all day. Hence, the system is equipped with a circuit with a specific intermittent working time. That is to say, considering the desired value, which is 20 minutes, the system is on for 20 minutes and then 20 minutes off while batteries have been considered as the main supply. The system intermittently turns on and off until batteries are out of charge or the main supply is connected; on this basis, NE555 has been used to reduce circuit consumption.

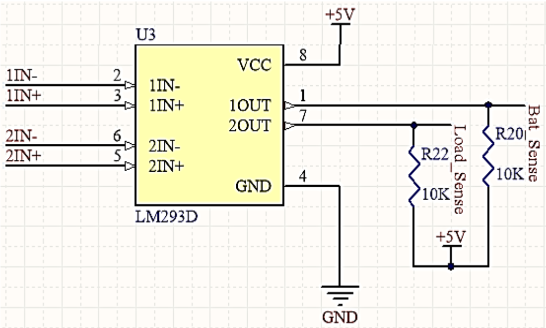

Figure 10. Comparator circuit that samples the output of two inputs of the power supply circuit; outputs 1 and 2 indicate activation of battery (secondary power) and solar panel (primary power), respectively

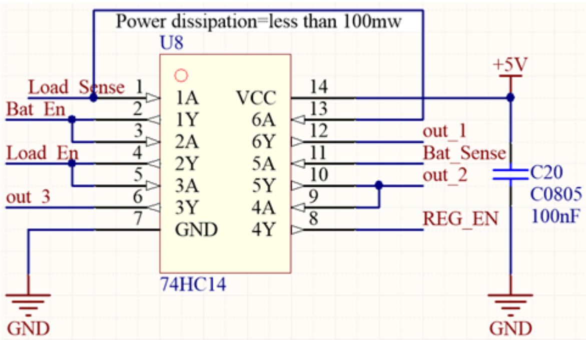

Figure 11. If the primary power supply (1A) is active, the battery output circuit (1Y) is deactivated and (2Y) activates the primary power supply

As shown in Figure 12, NE555 will be activated following the activation of U6, and the output of the component will activate the circuit output. The third supply will be activated whenever both input currents (panels and batteries) are deactivated, according to Figure 13. When out1 and out2 are activated, the third output will be activated. SHDN base of the regulator has been used to minimize the leak current within the range of 10 uA.

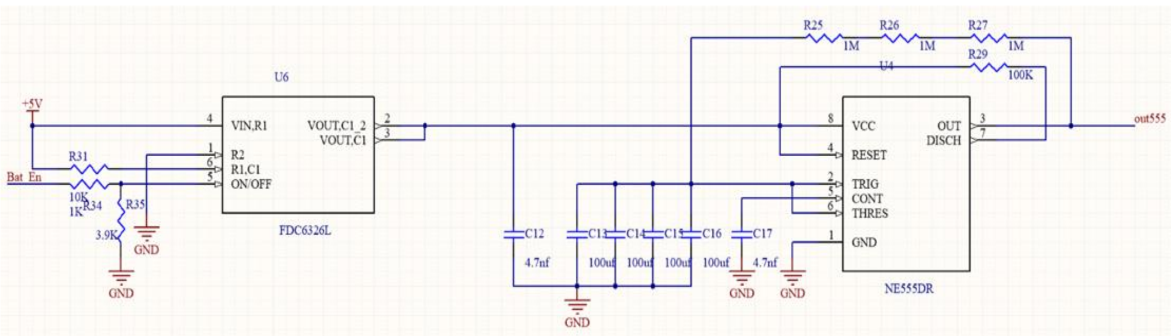

Figure 12. NE555 control circuit for making an alternating circuit

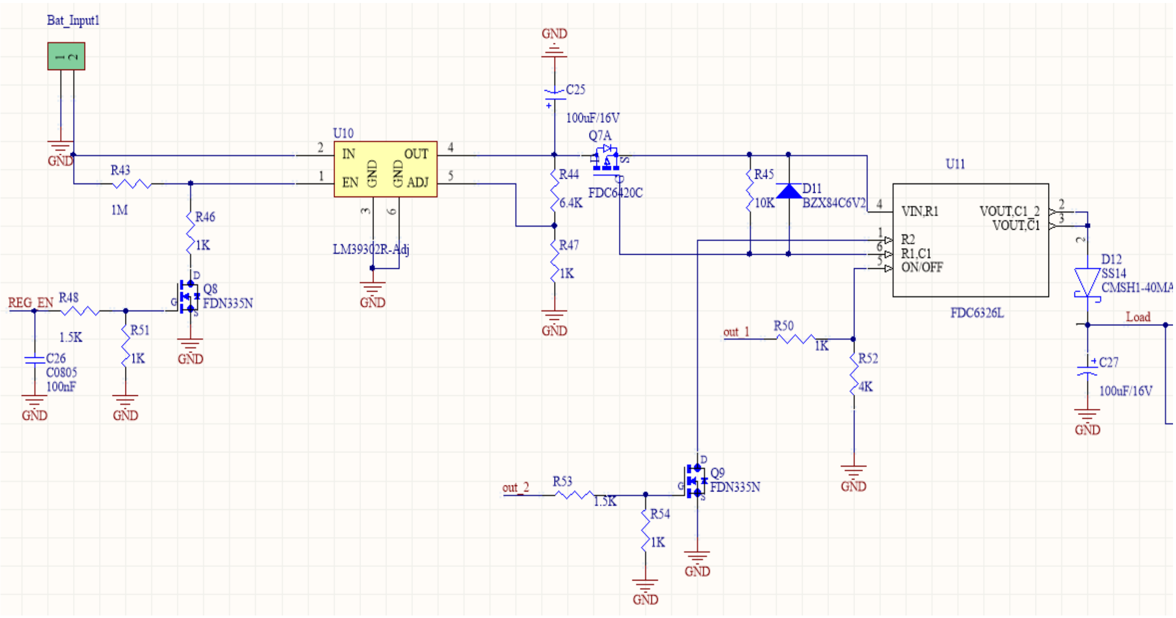

Figure 13. Third supply circuit

A boost has been used in system output to increase system efficiency. This circuit makes the circuit performance exceed 24 hours in tests in battery mode. Moreover, if necessary, a current controller has been used in the circuit output to increase or decrease the output voltage and current. As shown in Figure 14, using LT1073, circuit output has been increased up to 15 V in order to maximize the battery's efficiency.

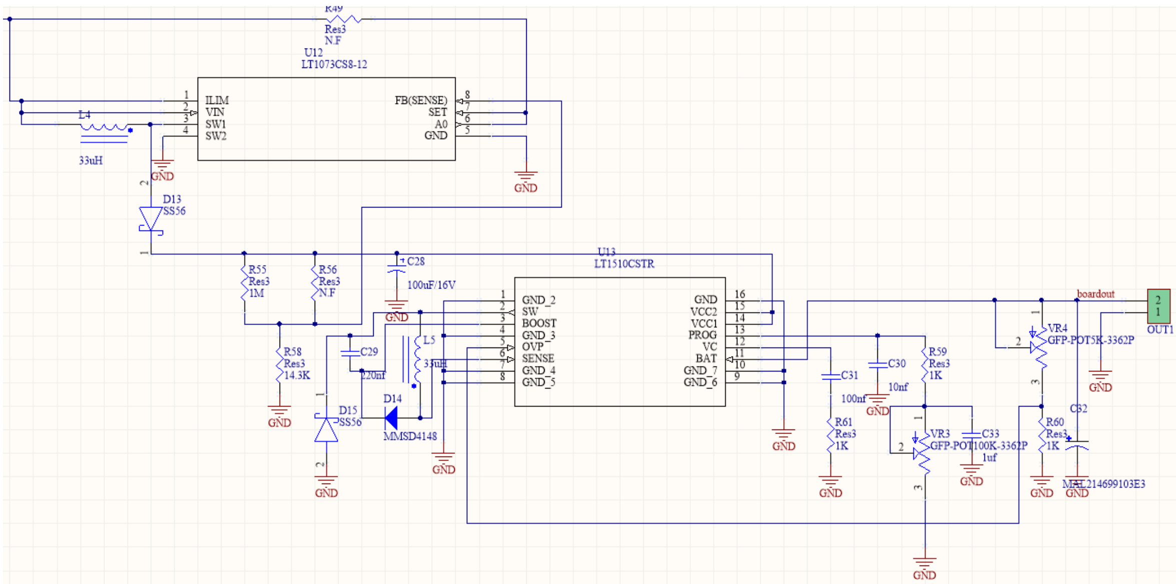

Figure 14. The circuit of the amplifier section and the output current controller

LT1510 has been used within the final output to control the final output current. A reducing regulator has been used to supply the circuit. Also, because the circuit can work in the worst possible state, a 5 V power supply is provided from two inputs; therefore, according to Figure 15, LTC4412 is used for this purpose. Two inputs meet a 5 V power supply to make the circuit capable of working within most downside cases; therefore, LTC4412 has been used, as shown in Figure 15.

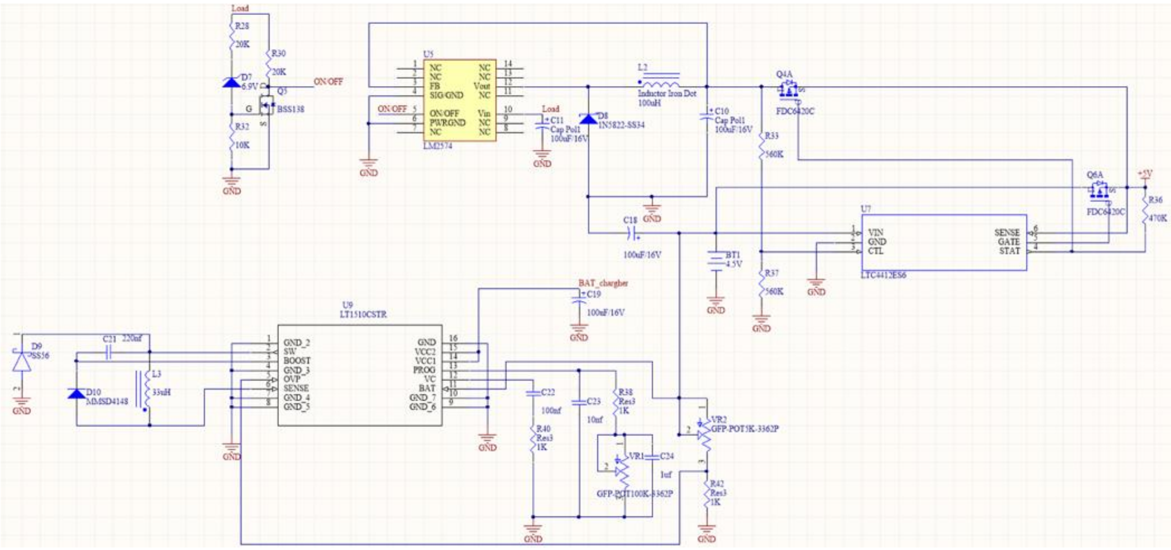

Figure 15. 5 V power supply circuit

4. FUNCTIONAL TEST RESULTS

As shown in Figures 16 and 17, the bottom board, which is located on the heat sink, has been considered as two inlets of the power supply circuit. 1,000 uF capacitor, as a supercapacitor within the primary power supply, causes the panels to be under less pressure and also is the main circuit supply. Another circuit has also been considered to charge batteries to which connector batteries are connected. NTC resistors can be used to protect the batteries but they are not used in this article. A heat sink has been used as a cooler to dissipate the temperature and increase the circuit efficiency. Boards are designed in two parts to reduce the board dimensions, and also circuits are connected to each other with a cable. The upper circuit is responsible for controlling the system and current control sections. Batteries were charged within 3 hours of conducted tests. The charging current was around 900 mA in most cases, which decreased over time. Anyway, the charging time is almost constant as the current decreases since the charging time is fixed by the internal timer of the circuit. For example, when the maximum current is 500 mA, batteries are charged for a longer time. Figure 18 shows the time required to charge 3 lithium batteries with a capacity of 2,200 mA, which is in parallel and is charged with different currents. Output load current was limited to 250 mA; the potentiometers of the board make it possible to set voltage and current on 0 to 12 V and 0 to 1.5 A, respectively. Output voltage and current were considered to be about 9 V and 250 mA within the test mentioned above. Considering the mentioned issues, after the batteries were charged, the system was turned off for 40 minutes and then was on and off every 20 minutes following the initial power cut. Batteries were still capable of supplying the output system after 24 hours. The designed boost circuit was able to improve the system efficiency significantly. Whenever the second power supply is cut, the third one can supply the system output. The time period of changing the state from the first to the second power supply and vice versa is in the range of ms, so it does not cause any disturbance in system output.

Figure 16. System power board

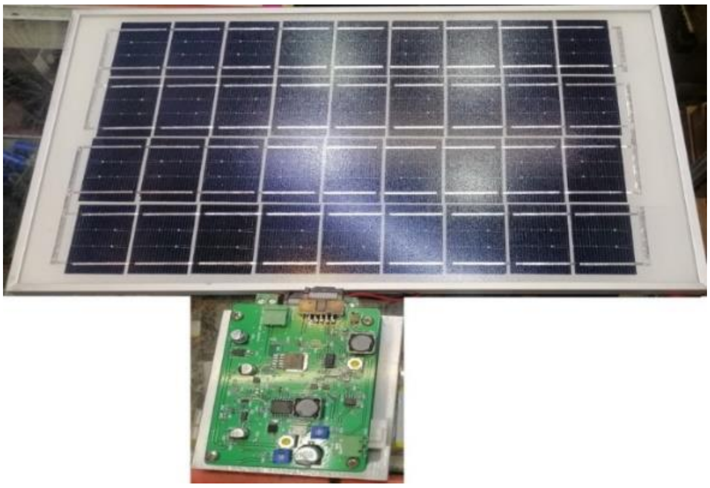

Figure 17. Designed circuit connected to the panel

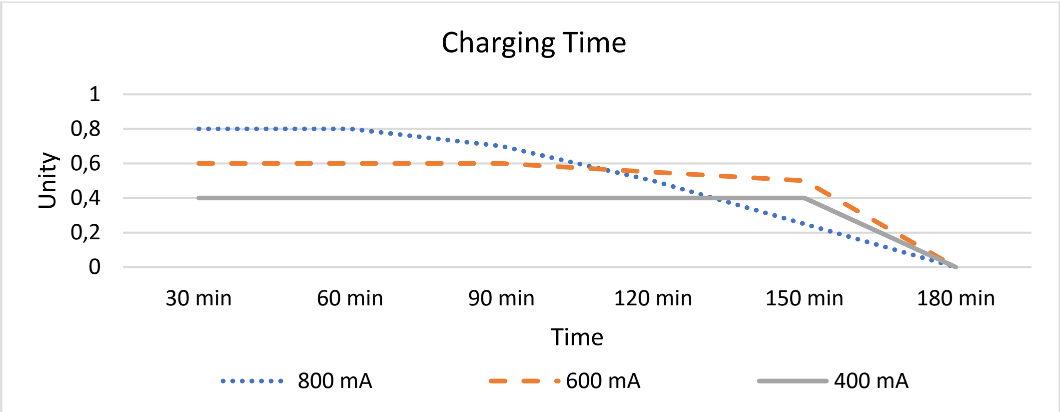

Figure 18. Chart of charging time of batteries with different currents

5. CONCLUSION

Mobile robots are experiencing a noticeable sharp trend in their usage. Most of them are equipped with batteries for their power source. Therefore, the batteries must be recharged rapidly. This process not only decreases the life span of batteries but also has negative impacts on their popularity as well as their performance. Consequently, by utilizing solar panels, their reliability is increased. The main superlative merit of the solar panel is that the volume which is occupied is not bulky. Moreover, they are manufactured in different shapes, and they are flexible. These features make them mountable on many mobile robots. From other points of view, solar panels are able to be substituted by a charger that makes mobile robots more functional. Solar panels have many advantages; however, they have their own weak points. The angle of irritation, along with myriad climates, affects efficiency, and as a result, these parameters limit the usage of PVs. In this paper, by introducing an intelligent board, which is portable and mountable under the PVs, different input voltages are selected based on a defined sequence by an internal circuit that has minimum power consumption. This board is also facilitated with a low illumination detector which is designed in batteries charger side that soar efficiency in the case of lack of illumination. In addition, the board is also equipped with features such as reverse voltage protection in its inputs, protection against short current status, and overheating. The output current is also confided with a variable potentiometer, and with the aid of a boost circuit, the working hours markedly increase from 16 to 24 hours.

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BIOGRAPHIES OF AUTHORS

Ali Jebelli received his master's degree and Ph.D. in Electrical and Computer Engineering from the University of Ottawa in 2014 and 2016. During his studies at the University of Ottawa, he worked as a research assistant and teacher assistant in the Department of Mechanical Engineering and the School of Electrical Engineering and Computer Science, and during that time, he won several prestigious awards. He also received a master's degree (MEng) in Electrical–Mechatronics and Automatic Control from the Universiti Teknologi Malaysia in 2009, and his bachelor's degree in electrical power engineering in 2005. His research interests include autonomous systems, intelligent control, robotics, mechatronics, electric motors drive, and solar and wind energy. He has authored or co-authored over 100 publications on these topics in international journals and referred conferences. Dr. Jebelli is currently leading the RoboticC Inc group, a team interested in building agricultural robots to increase the quality and quantity of products and designing autonomous vehicles and drones. Prior to this position, he completed three post-doctoral positions: the first with the Departments of Electrical Engineering and Computer Science and Mechanical Engineering at the University of Ottawa and the second with the Department of Electronics at Carleton University, and the third with the Department of Mechanical Engineering at the University of Alberta. He can be contacted at ali.jebelli@ieee.org.

Arezoo Mahabadi is currently a graduate student at Shahed University. Arezoo received her B.Eng. degree with Honors in Basic Engineering Science from the University of Tehran in 2019. Her research interests include intelligent systems, robotics, mechatronics, mathematical modeling of stationary fields, computational electromagnetics solar energy systems, sonar and radar systems, electric motor drives, and energy storage and management. She is currently the supervisor of the engineering department at RoboticC Inc. She can be contacted at a.mah.abadi@ut.ac.ir.