Two-Dimensional Movement Photovoltaic Cleaning Robot with Speed Control

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Abstract—**Numerous countries desire solar as alternative way of generating clean energy. However, the efficiency of energy produced by photovoltaic panels is influenced by the accumulation of dust. Additionally, current labor-based cleaning methods for photovoltaic arrays are pricey. These complaints lead to the need for continuous cleaning of the surface of PV panels. This study presents a new design for a robot which is used to clean a solar cell in large farms and photovoltaic arrays to increase its efficiency. The design model was made using Solid Work, and then a simulation of this design was done through MATLAB program. The force of the robot arm's impact on the cell, and its speed which are required to clean the cell, are the most important factors that have been focused on and controlled so as not to damage the cell. The results of the design simulation were close to the results based on theoretical equations describing the movement of this robot. A unit step response is verified to robot arm velocity. To control the robot, a specific simulated control method was used. The study shows that it is appreciated not only regarding of costing reduction, but also in term of reducing the force acting on a solar panel by controlling the speed of the robot arm. On the other hand, the root locus displays the stability of this design.**

Index Terms—**prismatic and revolute joints, photovoltaic cell, position and speed control, robot arm, tilting angle**

I. INTRODUCTION

Robotics technology has constantly been developed in recent years with numerous pieces of research have been conducted to develop cleaning robots with the goal of carrying out various tasks. Currently, the worldwide trends are to simplify a PV panel cleaning mechanism. The energy performance of the photovoltaic (PV) is determined by various factors which include weather conditions, material, and the panel size [1]. The power generation capacity of the PV might be reduced by 50% [2]. Therefore, automatic mechanisms have been designed for PV cleaning panels and reducing a human effort [3]. Recently, many research have addressed this field. One of them, depending on a clean module alone used a vacuum pump to spray the cleaning fluid [4]. Another research, robot works using a camera which tests ventilation and AC ducts [5]. In this research, the self-moving robot design is considered for areas with many solar cells avoiding excessive cost, time, and effort of confining the movement of the robot as it is in most of the published research. The researcher, Akyazi, Ömür, et al. [6], explored the facilitation of the cleaning of the dust materials accumulated and formed on the PV panel surface. They used a control device as a microprocessor. The designed robot completes the cleaning process automatically with limit and distance sensors. The Aluminum sigma profiles used as a frame and a rail system provide the advantage of lightness to the robot. Another research has been studied the walking mechanism of the cleaning robot such as cruciform structure. The research is carried out taken in regard two aspects, the mechanical analysis and the finite element analysis. The reliability, including anti-slipping, anti-overturning, and anti-twisting is researched based on the mechanical model, whereas the influence of the mechanical load is studied by the finite element model of the PV module [7].

In Thailand, the solar panel cleaning robot is designed and developed by studying its movement. Wireless Joystick, Sensor Sonar using Gear Motor and ARDUINO microcontroller were used. The robot cleans a solar cell by using a rotary brush with water spray to improve the cleaning system. It used gear motor which can operate at a surface level of 0-30 degrees Celsius. its results were about 80% cleaning ability by using rotary brush [8].

K Chailoet and E Pengwang [9] designed a universal module for transmission and manipulation that could be utilized with a different length of solar panels and different arrangements in a solar panel. Its cleaning depends on water, spiral brush, and rubber sweeper. The modular concepts were validated for the solar panel with a range of 1 to 4 meters in both testing and fielding environments.

In order to solve solar panels efficiency due to accumulated dust problem, the technique for dust removal system employing the Internet of things IoT is discussed. This is one of the papers that develops the simple and useful dust cleaning device and upgrades novel architecture of dust cleaning system for PV panel using IoT [10]. Most studies in this field concentrated on the efficiency of PV power according to the accumulated dusts

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and PV's tilting angles or comparing between the robot velocity with PV efficiency [11]. They are also interested in the effect of different robot end effectors with PV power [12]. The first ever robotized system for cleaning photovoltaic panel arrays at a large-scale solar park is presented. The PV Cleaner Robot consists of two motorized trolleys plus a cleaning head motivated by a belt and pulley system. The cleaning head is designed to clean while moving upwards and downward. It is made up of two sets of sprayers to put the cleaning solution, two rotating cylindrical brushes to scrub the photovoltaic panels, a scraper to remove the dirty solution, and directs it away from the panels that have been cleaned [13]. Our participation takes into consideration controlling the speed of the robot arm to prevent PV panels from being damaged in different areas regardless of the efficiency of these panels.

In this paper, we present a novel self-guided mobile robot for cleaning PVP panels in real-time without requiring any special hardware In order to pursue the realization of self-guided autonomous mobile robot platform, the fulfillment of several important targets have to be considered during this research such as high cleaning efficiency, reduction the costs, and minimizing the energy consumption. According to the state-of-the art, the main contributions of the paper can be briefly described as follows: (i) the new design is based on cleaning a large group of cells without need a robot system for each cell. Other researches rely on a slider or brush system that is moved from cell to cell manually. In the proposed platform, the system is moving automatically; (ii) the robot platform does not require any attached guide rails to move on the PVP. Therefore, the robot is fully autonomous on unstructured environment; (iii) unlike other systems where the rotation of the brush could create uncontrolled dispersion of the removed sand on previous cleaned regions, the proposed system combined with motion and cleaning strategies has ability to regulate the sand removing without any re-deposition; (iv) the real-time motion control of the robot position is the design key for the autonomous drive of the robot. As a consequence, due to the regularity of the area to be cleaned and to the proposed motion strategy, the robot does not require a path recognition obtained by different techniques such as the mobile robot navigation, Path Planning and Motion Coordination and a set of wireless sensor networks or vision sensors; (vi) the proposed robot can be position controlled based on any tilting angle panels and the position and velocity of the robot arm could be adjusted according to the desired tilting angle values.

The rest of this paper is organized in accordance with the following sections: In section 2, a short overview of new robot design with specific dimensions have been selected. Section 3 describes the derivation of mathematical equations of this design. The selected PV panel that the design was made based on is presented in section 4. In section 5, the simulation results are validated using MATLAB Simulink such as robot position, velocity and applied force. Section 6 includes the evaluation results for a unit step response of robot arm speed. Finally, in section 7, the conclusions of this work are presented.

II. Robot Mechanical Design

With rising cost of electricity and concern for the environmental impact of fossil fuels, implementation of eco-friendly energy sources which are similar solar power is growing. One of the main problems of photovoltaic (PV) efficiency is soil and dust particles which are accumulated reducing the solar energy, thereby, falling overall power performance.

Since this robot is designed to clean the panels in solar cell farms and PV arrays, the robot wheels are strictly selected to suit rough surface location. The robot consists of the base, two arms and one wiper. The first arm is welded to the base as well as it is connected to the second arm by joints. One of the main objectives of motion modeling of mechanisms is the design of simplified or pilot model. Consequently, this model has been drawn using solid work program. Solid modeling is currently the main method to create new structures of engineering products and modernize the existing ones. The advantages of solid modeling systems like SolidWorks are realistic visual representation of the future product. Fig. 1 illustrates 3D model of the robot.

Figure 1. Robot design

A. Material Selection and Mass Optimization

Mass studies are important for many reasons; the main reason is the power consumption. In order to reduce the mass, many alternatives were touched on like hollow links. Aluminum material is selected for this design because it doesn't need to empty the links to maintain the strength and deflection resistance.

B. Dimensions Selection

The chosen dimensions are based on the space between cells. So as to move and clean easily. In order to take advantages of the U space of the base which facilitates installing battery, motors, and other components.

Table I displays Aluminum properties such as density, shear and modulus of elasticity. Also, it clarifies the robot's mass, volume area and surfaces area. These values generated by solid work program according to the dimensions which are selected for this design.

TABLE I. ALUMINIUM PROPERTIES AND ROBOT DIMENSIONS

Parameter	Value	Unit
Density	2700	kg/m3
Shear Modulus	25	GPa
Modulus of Elasticity E	69	GPa
Robot mass	115.83601	kg
Arm mass	1.75419	kg
Robot volume	42.90223	m3
Arm volume	0.64970	m3
Robot surface area	190.2057	m2
Arm surface area	7.6453	m2

C. Robot Mechanical Parts

The base is modeled in a U shape to sustain some mechanical and electrical parts and cleaning components. It is attached to the wheels at the bottom. Two of the wheels are driven by motors, whereas, the front wheel is manual. The base thickness is selected to be robust to avert bending due to weight. The rotary plate is connected to the base at the top. It connects to the first link through pin connection. It is shaped with fillets to reduce the stress concentration points. The two links are designed to allow up and down motion. Also, they are permitted to reach an angled position of the PV cell which make a perfect contact while cleaning.

The wiper is the end effector of robot's arm. Its dimensions were chosen based on the size of the solar cell which was selected for this research. It was designed with a low thickness which decreases the affecting load on the cell as well as increases the cleaning process. There are diverse shapes of cleaners used for this purpose. Some of those are serrated, brush, and other patterns. In this paper, the cleaner is chosen for it is softer on the cell, does not cause scratches, and easier to move compared to other designs.

III. MATHEMATICAL MODEL OF THE SYSTEM

The robot has two degrees of freedom. The movement is defined by two independent variables. These variables are x and θ. Therefore, the system has two governing equations to describe its motion.

Total mass of the robot moves together in x-axis. The total mass of robot, including of base, links, wiper and motors. The source of input force which acts stim on this mass from motors. The robot has two servomotors for two driving rear wheels. In addition, the robot has front free wheel. The equations of motion below explain the robot movement. All values are carefully selected. Equation 1 shows the base movement in one direction. The total robot mass effects are on robot displacement. Not only the motors and mass affect movement, but also friction force is taken in consideration. The robot walks on soil and gravel road. This road is not smooth all the time. Therefore, the friction will impede robot movement.

$$(M + m_1 + m_2)\,\ddot{x} + b\dot{x} + R_2 = F_i \quad (1)$$

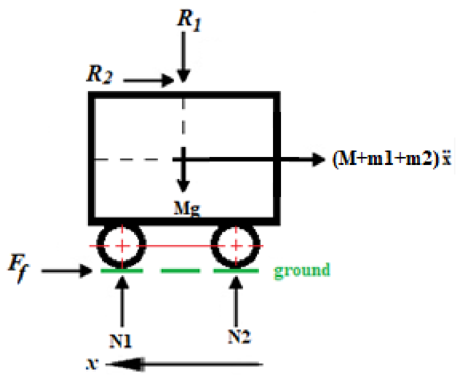

Figure 2. Base robot free body diagram.

Fig. 2 shows the R_1 normal force of the robot is equivalent to robot's weight. The second equation describes link and cleaner movement. These two parts moves together with angular velocity $\dot{\theta}$ and angular acceleration $\ddot{\theta}$. The motor torque of stepper motor gives this arm moment to rotate. In addition, the friction force between the joints appears in Fig 3. The moment about center of mass of this link is illustrated in (2) assumes that the counter clockwise direction is positive.

$$m_2 l^2 \ddot{\theta} + R_3 \frac{l}{2} sin\theta - R_4 \frac{l}{2} cos\theta + R_1 \frac{l}{2} sin\theta - R_2 \frac{l}{2} cos\theta = 0 \quad (2)$$

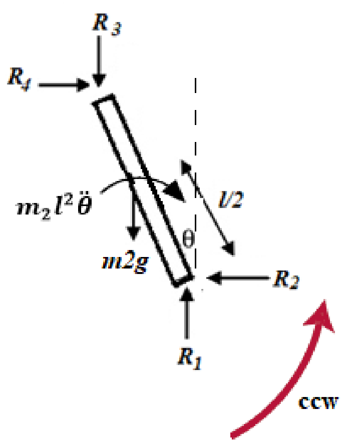

Figure 3. The first link free body diagram.

The cleaner free body diagram shown in Fig. 4 is tilting with an angle φ and having a mass m_2. The moment equation at center of mass shown below.

$$m_2 l^2 \ddot{\varphi} + R_3 \frac{l}{2} sin\varphi + R_4 \frac{l}{2} cos\varphi = 0 \tag{3}$$

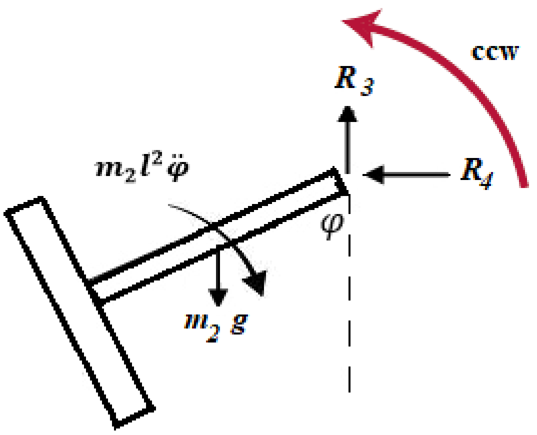

Figure 4. The cleaner free body diagram.

As shown in (1), friction force between the wheels and road depends on the kinetic friction coefficient and the normal force of robot. The motor torque is calculated by using (4). The motor torque depends on robot weight and the wheel's radius for the total robot mass. Also, the torque required to rotate the robot arm is computed using the same principle, but the arm weight only is considered here.

$$T = J\dot{\omega} + c\omega \tag{4}$$

T is the motor torque. J is the motor inertia. C is the motor damping coefficient. ω is the motor angular speed that's equal to the derivative of motor angle.

The robot is designed to work in large solar cell farms. The design is selected to fit a specific solar cell. Ultra-efficient polycrystalline is used in fabricating the solar panel. Fig. 5 shows the solar panel specifications and its dimensions. Dimensions are in mm.

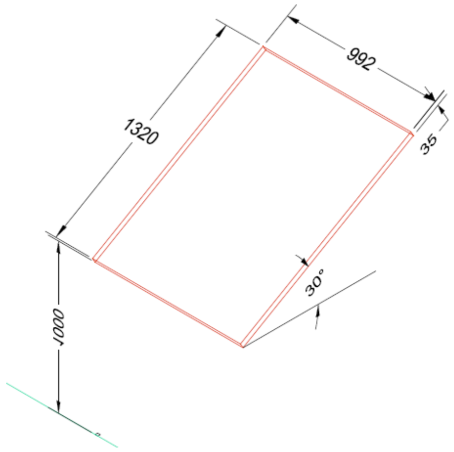

Figure 5. Solar panel dimensions

The position of the designed robot can be controlled depending on any tilting angle panels. Employing the Simulink, we can adjust the position and velocity of the robot arm according to the desired values. This is one of the features of this design. In this research, the selected panel in Fig. 5 is presented as a case with 30° tilting angle.

IV. Simulation and Results

The design of the presented system is formulated by using solid work and simulated as well as MATLAB program. The system is able to move along x axis for a specific time and stop to move the cleaner link along the PV panel with a controlled velocity in order to protect the PV panel from breakage, as well as the angle is controlled to move along PV panel. The motors torque is applied to move a robot cart.

Fig. 6 reveals the block model that is simulated in MATLAB. X path signal is the cart path during the first 5 seconds. This signal turns into physical signal which is an input to a prismatic joint. Angle signal is the cleaner path during the last 5 seconds of motion. Also, it turns into physical signal and enters to revolute joint. The results are displayed in two scopes as in Fig. 7 and 8. The cart motion (displacement and velocity) is shown in Fig. 7. The cleaner analysis (position and velocity) is shown in Fig. 8. The 30° angle has been selected as a desired angle φ.

The Simulink block is generated by the solid work. Signal 1 is the input signal for robot cart to move horizontally during the first 5 seconds and then stop. The prismatic joint (linear motion joint) is made up of a moving surface that slides linearly along a fixed a surface. The main criterion for evaluating prismatic joints is the stiffness-to-weight ratio. Achieving a good stiffness-to-weight ratio requires the use of hollow structure for the moving elements rather than the solid rods. Signal 2 is the input signal to the rotational robot arm to move along the PV panel surface with 30° degrees in the last 5 seconds of motion. The revolute joint (rotary motion) is used to allow pure rotation while minimizing radial and axial motions. The movement of robot from initial position to final one is displayed in Fig 9. Front, top, right and isometeric views of this design are presented in Fig 10.

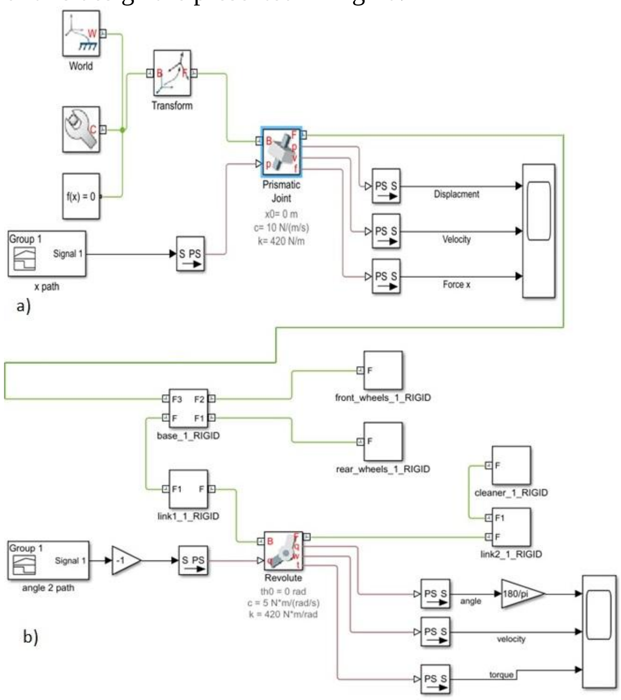

Figure 6. Block diagram of the designed robot. (a) Cart horizontal path (b) robot arm movement with 30o angle

Some of blocks in Fig 6 are generated automatically when the simulated calling the Solid work. Then these blocks were connected together by adding some blocks to convert the physical signal into unitless Simulink output signal. Also, a prismatic joint between two frames is used. This joint has one translational degree of freedom represented by one prismatic primitive. The joint constrains the follower origin to translate along the base z-axis, while the base and follower axes remain aligned. A revolute joint acting between two frames. This joint has one rotational degree of freedom represented by one revolute primitive. The joint constrains the origins of the two frames to be coincident and the z-axes of the base and follower frames to be coincident, while the follower x-axis and y-axis can rotate around the z-axis.

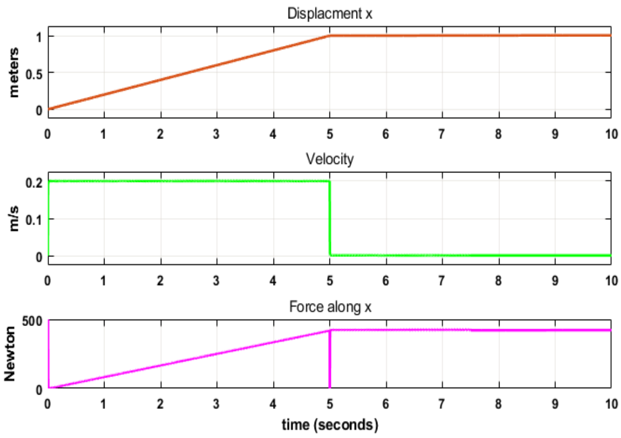

Figure 7. The robot cart response, velocity and the motor force acting on it.

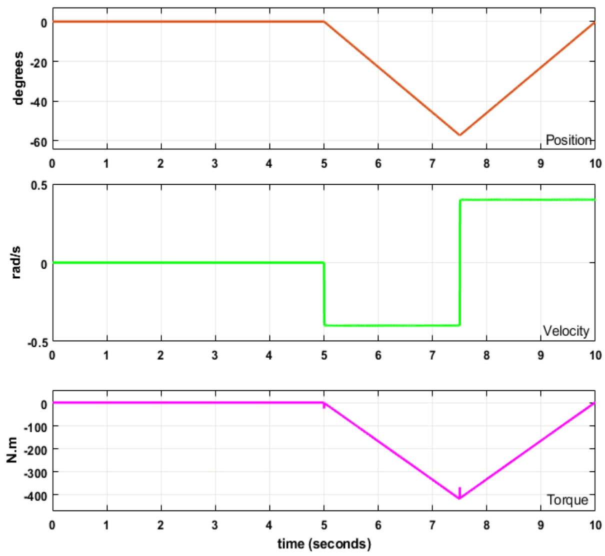

Figure 8. The cleaner link position, angular velocity and the stepper motor torque

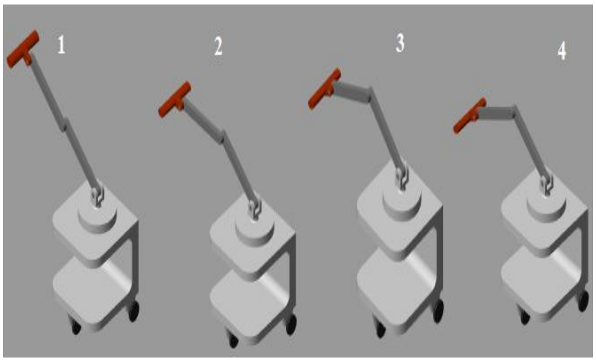

Figure 9. Steps of robot movement

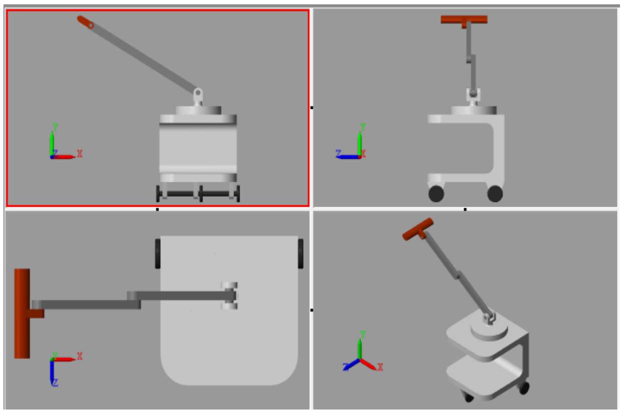

Figure 10. Views of robot design

V. System Control

The performance of a control system is identified in terms of the transient response to a unit-step input. The dynamic behavior of the second-order system can then be descripted in terms of two parameters ζ and ω_n.

The response of a system to a unit-step input depends on the system initial conditions. It is a public practice to use the standard at rest of the system initial condition is with the output and all-time derivatives thereof zero [14].

A unit step input is employed to evaluate the arm response. The open loop transfer function of the robot arm is:

$$\frac{1}{1.754\, s^2+8.603\, s+20000} \tag{5}$$

The initial conditions are assumed to be zero. The unit step response of the robot arm is shown in Fig. 11. The system is underdamped second order response. The natural frequency and damping ratio are mentioned in table 2. It can reduce the steady state error and system overshoot as well as decrease the settling time of the system by adding a PID controller to enhance the system performance.

The performance of a feedback control system can be defined in terms of the location of the poles of system in the s-plane. A graph displaying how the poles of the characteristic equation moves around the s-plane as a single parameter diverges is known as a root locus plot. The root locus is a useful tool for designing and analyzing feedback control systems. In this paper, MATLAB tool is used for obtaining a sketch of a root locus plot for robot arm as it is represented in Fig. 12 [11]. This figure shows all system poles on the left-hand side of s-plane, so the system is stable. The root locus figure representing the asymptotes are vertical and parallel to the imaginary axis, however, the system is stable for all values of controller gain. The root locus doesn't cross the imaginary axis.

This system has a type zero control system. Therefore, there is a steady state error equal to $\frac{1}{1+K_p}$ where K_p is the position error constant.

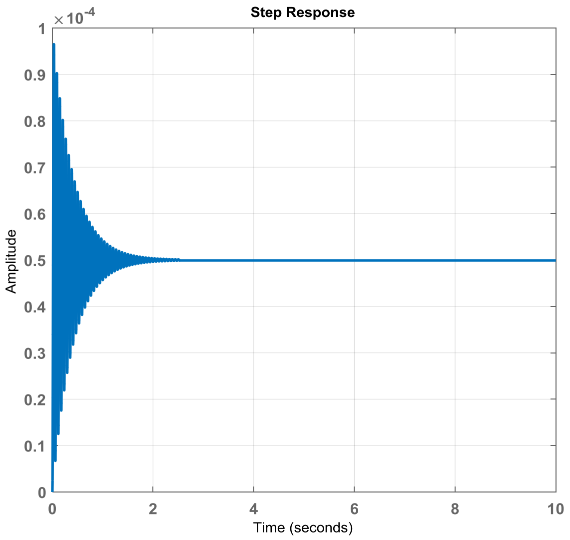

Figure 11. Step response of robot arm

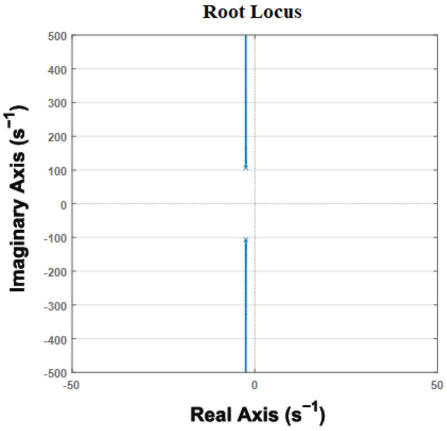

Figure 12. Root locus of robot arm unit step response

In order to enhance the response of the robot arm, more than one optimization method is used in addition to making use of different types of controllers as Fig. 13 and Fig. 14 show. Then, compare each method results to select the best one for our design.

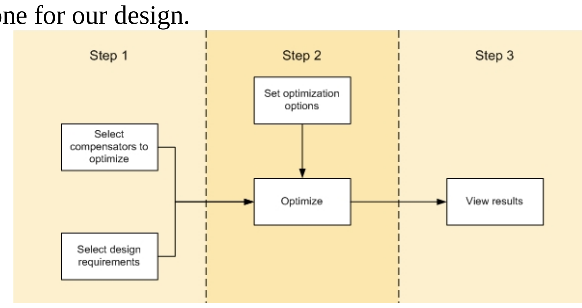

Figure 13. Flow chart of different optimization methods.

TABLE II. PERFORMNACE OF ARM STEP RESPONSE USING PID CONTROLLER.

Settling time	Over-shoot	Damping ratio	Natural frequency	Peak time	Max. peak	Time constant
1.5898 sec	93.0372%	0.0231	1.07rad/s	0.0294 sec	9.6514e-05	4.08e-01
3.5735 sec	-	>1	1.07rad/s	9.6338	1.0000	-

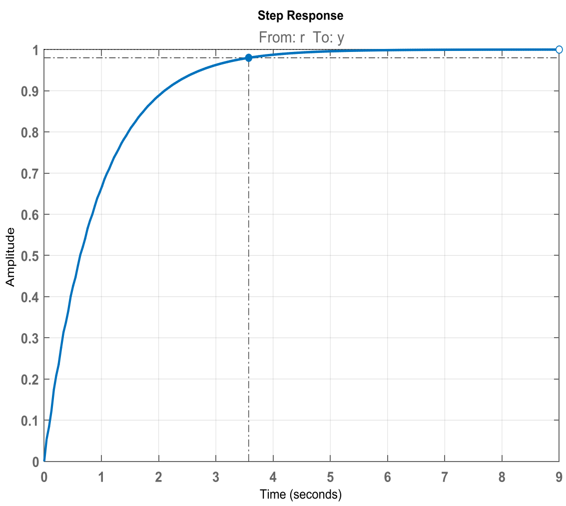

Figure 14. Robust response time after adding PID controller

VI. CONCLUSION

This paper has presented the design, modeling and simulation with two DOF PV cleaning robot. It is capable of overcoming some major problems faced by the earlier developed cleaning robots. The main advantage of the proposed robot is that it can be used to clean the solar cells in a wide area as well as it is capable of moving in both the translational and rotational motion. In addition, it is controlled to accommodate different variables such as tilt angle, robot position and speed. The range of the tilting angle is limited to 0 °and 30 °. The cart velocity is between 0 m/s and 0.2 m/s, and the arm angular velocity is between – 0.4 rad/s (cw) and 0.4 rad/s (ccw) which the arm moves up and down along PV panel. One of the disadvantages here is the size of the robot which is considered rather large, but this problem will be overcome by optimization and further analysis in the future.

On the other hand, this design reduces the number of labors. So, the time and cost fall compared with other designs. These features are not the only advantages, but also a camera or sensor on the robot arm can be added. This component works as a sensor to measure the amount of dust in order to increase the velocity of the arm to make the solar cell cleaner as much as possible taking in to account the force required for that to prevent solar cells from damage.

CONFLICT OF INTEREST

The author declares that there are no conflicts of interest regarding the publication of this article.

AUTHOR CONTRIBUTIONS

Ayat A. Al-Jarrah designed and directed the idea. Rami A. and Fadwa W. designed the model. Ayat A. Al-Jarrah and Rami A. carried out the simulation. Ayat A. Al-Jarrah, Rami A. and Mohammad A. added the design and implementation of the research, discussed the results and contributed to the final manuscript. Ayat A. Al-Jarrah and Manar H. took the lead of writing the manuscript.

NOMENCLATURE

b	Friction coefficient between the robot wheels and the ground
Fi	Input force from motors
$l1$	First link length
$l2$	Cleaner link length
M	Base robot mass
m1	First link mass
m2	Cleaner mass
R	Reaction Force or Normal Force
r	Wheel radius
x	The base displacement
φ	The angle of rotation for the cleaner link
θ	The angle of rotation for the first link
AC	Air Conditioning
PV	Photovoltaic

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