

Highlights

Novel Cable-Driven Robot for Cleaning Solar Panels

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- Cable Driven Parallel Robot.
- Dynamic Model.
- Novel Design with single cable loops.

Novel Cable-Driven Robot for Cleaning Solar Panels

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Abstract

Nowadays, solar energy is one of the most common renewable energy sources for increasing the electrical energy demand. In this sense, researchers have focused on panel efficiency, maximum energy extraction, or control and power electronics. Efficiency of solar energy can be affected by two main factors: environmental, such as humidity, wind speed, precipitation or temperature, and non-environmental, like atmospheric pollution, dust accumulation and bird droppings. As the energy extracted from the sun is converted into electrical energy through solar panels, the main issue with non-environmental related factors is that they cause poor functionality, reducing the overall electrical power obtained. In this sense, solar panels require proper maintenance and cleaning. Most of the current labour-based cleaning methods for solar panels are costly in time, water and energy as well as lacking in automation capabilities. Tackling all that, this paper proposes a novel robotic cleaning device. This robotic device is based on a Cable-Driven Parallel Robot (CDPR) with a versatile platform, which is capable of travelling the whole length of the panels. The design of the CDPR allows the robot to reach all the panel area using one single cable loop to command the manoeuvres, and another single cable loop to control the cleaning method attached to the end-effector, which is a conventional car windscreen wiper.

Keywords: Cable-driven parallel robot, Single cable-loop, Kinematics, Dynamics, Workspace

1. Introduction

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The current energy crisis increasing worldwide is the main reason to look for cleaner, non-based fossil fuels, energy sources. In this sense, renewable energy is becoming an increasingly popular source of electricity worldwide, with photovoltaic solar energy at the forefront of this movement. Photovoltaic solar energy is generated by converting sunlight into electricity using solar panels. This renewable energy source offers a range of advantages, including reducing carbon emissions, providing a cost-effective alternative to traditional energy sources, and decreasing energy dependency. In this introduction, we will explore the advantages of using photovoltaic solar energy as a renewable energy source and highlight the importance of cleaning solar panels, as well as the emergence of automated systems for cleaning them in comparison to manual cleaning.

Advantages of using photovoltaic solar energy as a renewable energy source:

- **Reduced Carbon Footprint:** One of the primary benefits of photovoltaic solar energy is its ability to reduce carbon emissions. Solar energy does not release any greenhouse gases or pollutants into the environment, making it an excellent choice for reducing the carbon footprint. This is particularly important given the growing concern for climate change and the need to reduce global carbon emissions.
- **Cost-effective:** Another significant advantage of photovoltaic solar energy is its cost-effectiveness. While the initial installation cost may be higher than traditional energy sources, the long-term cost of solar energy is much lower due to its low maintenance requirements and the abundance of sunlight. Furthermore, the price of solar panels has decreased significantly over the years, making it a more accessible and affordable option for households and businesses alike.
- **Decreased Energy Dependency:** Using photovoltaic solar energy as a renewable energy source can reduce energy dependency on non-renewable

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sources such as fossil fuels. This can help decrease the reliance on imported energy sources and promote energy independence. Additionally, it can help diversify the energy mix, reducing the risk of supply disruptions and promoting energy security.

To ensure that photovoltaic solar energy is produced efficiently, it is essential to maintain the cleanliness of the solar panels. Dust, dirt, and debris can accumulate on the surface of the solar panels, reducing their ability to absorb sunlight and convert it into electricity. This can result in reduced efficiency and lower energy production. Therefore, regular cleaning of solar panels is necessary to maintain their efficiency and prolong their lifespan.

Traditionally, solar panels were manually cleaned using water and a brush. However, manual cleaning can be time-consuming, labor-intensive, and may not be practical for large-scale installations. With the advancement of technology, automated systems for cleaning solar panels have emerged. These systems use water, brushes, and other cleaning materials to clean solar panels automatically, reducing the time and effort required for manual cleaning. Furthermore, automated systems for cleaning solar panels are more efficient and can clean a large number of solar panels in a short periods, making them an excellent option for commercial and industrial settings.

In conclusion, photovoltaic solar energy offers a range of advantages as a renewable energy source, including reducing carbon emissions, providing a cost-effective alternative to traditional energy sources, and decreasing energy dependency. However, to maximize the efficiency of solar panels, it is important to keep them clean through regular maintenance. Automated systems for cleaning solar panels have emerged as a practical and efficient alternative to manual cleaning, reducing the time and effort required for maintaining the cleanliness of solar panels. By using photovoltaic solar energy coupled with automated cleaning systems, we can make a significant contribution towards a more sustainable energy future while promoting energy independence and security.

2. System description

In this work, the cleaning of the solar panels is conducted through a novel planar CDPR. The particular design of this robot involves two single closed cable-loops to command the movement of the robot together with the cleaning of the panels.

The following sections detail the CDPR principal elements, and present the nomenclature used in the mathematical models (Section 3).

2.1. Overall Description

As aforementioned, this work proposes a novel design for planar CDPR, which can be seen in Fig. 1. **POR AQUÍ**.

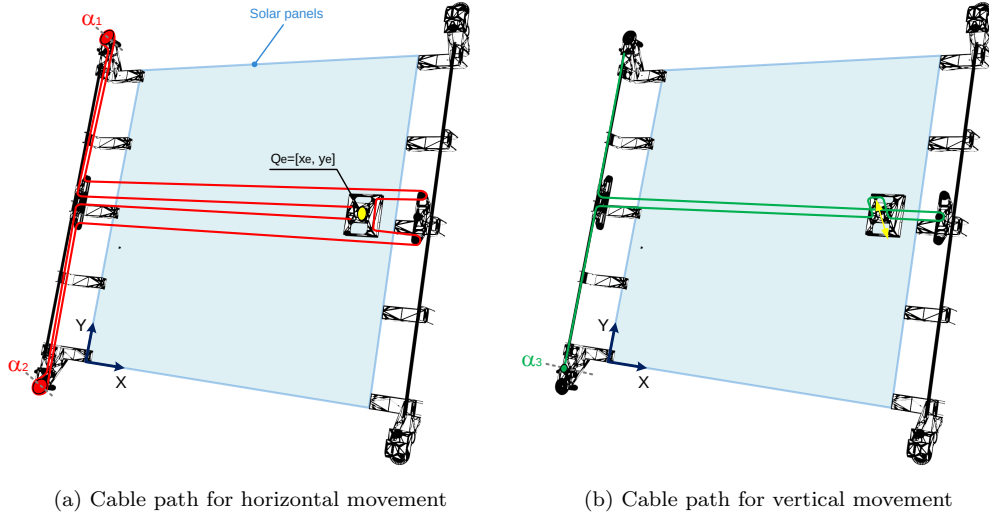


Figure 1: Scheme of the proposal

On the one hand, the proposal incorporates passive carriages with linear guides on the top and bottom parts of the frame. This addition has proved to provide some advantages, such as a bigger workspace, while increasing the mathematical complexity of the static and dynamic models (see **citar carros pasivos 1 y 2**).

In order to overcome the main drawback of this design, which is the poor stiffness along the x -axis, a single cable-loop is introduced to command the end-effector manoeuvres as shown in Fig. x. The use of this single cable-loop maintains the CDPR workspace increment, while reducing the motorization power required and the overall modelling complexity (see **citar uCDPR**).

Figure x shows a side-to-side comparison of workspaces between the novel design and a conventional planar CDPR design. In this sense, it is notable that the newest design provides x % more of working area than conventional CDPRs planar architectures. Additionally, due to the disposal of the frame

and its elements, the workspace provide by this robot is a prefect fit to the cleaning surface of solar panels.

On the other hand, Fig. x shows a second single closed cable-loop used to command the steam device attached to the end-effector. In this sense, the coordinate action of both single closed cable-loops entails the cleaning of the solar panels as the end-effector travels inside its workspace.

2.2. Nomenclature

Basado en el paper del closed loop

Figure x. shows the nomenclature used throughout this work, highlighting its most important elements: end-effector, frame and single closed cable-loops with different colours.

The dimensional parameters include: the width and height of the frame, W and H ; the width and height of the end-effector, w and h , the distance between the centre of mass of the end-effector and the centre of the driven pulley located at the top of the end-effector, a , and the distance between the centre and the bottom of the end-effector, b ; the width of both carriages, w_{uc} and w_{lc} , respectively; and the pulleys radius, r .

Additionally, in order to model the kinetostatic behaviour of the design through some assumptions detailed in the following section, the angles of the cables, α , β and γ , with regards to the y -axis of the lower, inner and outer paths of the cable-loop are also included in Fig. x.

It should be pointed out that this model employs generalised coordinates, being q_1 the horizontal coordinate of the end-effector, q_2 the angle with regards the y -axis of the end-effector, and q_3 and q_4 the horizontal coordinates of the lower and upper carriages, respectively. Finally, the input torque to the motors is noted as τ_1 and τ_2 , respectively.

3. Mathematical Model

This section presents the mathematical foundations of the novel CDPR design, including its kinematic, and static models.

Explicar por qué no hace falta el modelo dinámico: Vamos muy lentos (aceleración muy baja), por lo que los modos de vibración del sistema no se excitan haciendo posible el uso de control cinemático. Es decir, que no es necesario ya que no se va a aplicar control dinámico.

3.1. Kinematic Model

One of the advantages of the novel design is its kinematic model simplicity. The simplicity arises from the reduced number of actuators, just two, and the used of one single cable loop. In this sense, the kinematic model only takes into account the variation of end-effector position, Δx_e , Δy_e , with regards to the actuators movement, rolling up or out the cable, $\Delta\alpha_1$, $\Delta\alpha_2$.

On the one hand, the forward kinematic transform can be written as:

$$[\Delta x_e, \Delta y_e] = \phi_{FK}(\Delta\alpha_1, \Delta\alpha_2), \quad (1)$$

being $\phi_{FK} = [\frac{r(\Delta\alpha_1+\Delta\alpha_2)}{2}, \frac{r(\Delta\alpha_1-\Delta\alpha_2)}{2}]$.

On the other hand, the inverse kinematic transform is expressed as:

$$[\Delta\alpha_1, \Delta\alpha_2] = \phi_{IK}(\Delta x_e, \Delta y_e), \quad (2)$$

being $\phi_{IK} = [\frac{(\Delta x_e - \Delta y_e)}{r}, \frac{(\Delta x_e + \Delta y_e)}{r}]$.

The kinematics of the robot are not affected by the tension or pre-tension of the cables, as it only depends on the variation of end-effector pose, $\Delta x_e, \Delta y_e$, or angular position $\Delta\alpha_1, \Delta\alpha_2$, together with the pulleys radius, r . However, the tension of the system plays an important role in positioning accurately the robot.

The perpendicular movement to the plane, i.e., the movement of the cleaning weapon with respect to the panel is executed through a second closed cable-loop whose kinematic is **xxx**.

3.2. Static Model and Workspace Determination

The static model is developed under the assumption that both carriages remain almost aligned to the end-effector in the x -axis after each manoeuvre. Additionally, the cables angles, α , β and γ , are assumed to be small, and quasi-similar at both side of the end-effector, so the end-effector rotation is also small. Finally, since this proposal uses a single closed cable-loop to control the CDPR movements, whose length is considered constant, the forces exerted by the upper and lower cables on the end-effector are balanced. In other words, the vertical equilibrium is statically ensured.

On another note, the workspace of the robot is composed by the set of poses where the end-effector is statically stable [ref A. Pott]. Taking into account all of this, the novel CDPR workspace can be determined by the following set of equations:

$$\begin{array}{ccc} \frac{w_{lc}}{2} & \leq x \leq & W - \frac{w_{lc}}{2} \\ b & \leq y \leq & H - a \end{array} \quad (3)$$

with $[x, y]$ all the end-effector coordinates that satisfies equation (3). In this sense, the CDPR workspace is determined by the geometrical relation between the end-effector and the frame, which covers almost all the frame area. This enlarged workspace, allows the robot to reach every corner of the solar panel, which is demonstrated in Section (5.3).

4. Kinematic Control

This section proposed a simple kinematic control to prove the reachability of the end-effector within its workspace.

4.1. Control scheme

To illustrate the capacity of the novel design of reaching almost all the frame area, the kinematic control proposed in Fig. x is implemented. This kind of control only takes into account the dynamics of the actuators (see equation (4)), which are assumed to be decoupled from the CDPR.

$$\boldsymbol{\tau} = \mathbf{J}\ddot{\boldsymbol{\alpha}} + \mathbf{b}\dot{\boldsymbol{\alpha}} + r\mathbf{T} \quad (4)$$

with $\boldsymbol{\tau} = [\tau_1, \tau_2]^T$ the array of torques, $\mathbf{J}$ the rotational inertia matrix, $\boldsymbol{\alpha} = [\alpha_1, \alpha_2]^T$ the array of joint coordinates, and $\mathbf{b}$ the viscous friction coefficient of each actuator, respectively.

In Fig. x the end-effector position reference, $\mathbf{Q}_e^*$, is transform to the joint coordinates reference, $\boldsymbol{\alpha}^*$, by means of the inverse kinematic. The error signal $\boldsymbol{\varepsilon}$ is reduced as much as possible by tuning appropriately the controller block, $\mathbf{R}$, which is implemented using joint coordinates control, and yields:

$$\mathbf{R} = \begin{bmatrix} R_1 & 0 \\ 0 & R_2 \end{bmatrix} \quad (5)$$

being $R_1 = R_2 = R$ due to the mechanical symmetry of the design. One advantage of implementing the control strategy in the joint coordinates space is that SISO controllers can be tuned for each motor.

4.2. Controllers tuning

The controllers are tuned ensuring a high performance trajectory tracking, with a fast response, no overshoot and zero steady state error. In this sense, we found that **PID** controllers fulfil all the requirements mentioned above.

Assuming the correspondent linear transfer function of each motor, $G(s) = \frac{1/J}{s \cdot (s + J/b)}$, the PID controllers can be tuned following the frequency domain technique described in [ref 33 paper offset].

On the one hand, the PID proportional, K_p , and derivative, K_d , gains are selected setting appropriated values of the gain crossover frequency, ω_c , and the phase margin, φ_m . However, the integral gain, K_i , is set to ensure the fulfilment of the control requirements.

On the other hand, the values of the rotational inertia J , and the viscous friction coefficient b of each motor, are identified following the well-known procedure based on the speed step response, discussed in more detail in [1].

5. Novel Design Validation

In this section, first the experimental platform is described, including its main elements and the vision system employed to validate the results. Then, by means of the software Matlab® the CDPR is modelled and some simulations carried out. Finally, the kinematic control is tested in the real platform proving the reachability of the novel design and its appliance to the cleaning of solar panels.

5.1. Robot and Vision System Description

The experimental platform is designed to be mainly laser cut and 3D printed. Figure 2 shows the prototype.

The frame is made of technical aluminium 45 mm × 45 mm, the passive carriages and end-effector are made of steel cut by laser. The driver pulleys are of steel and laser cut, while the driven pulleys are 3D printed with micro carbon fibre-filled with nylon (see details in Fig. 3c). The main closed cable-loop is a 2 mm diameter steel cable, and the z -axis is a 1 mm diameter steel cable. Additionally, the passive carriages are mounted on HIWING EG Series-Ball Type Linear Guides attached to the frame.

The actuators are three Maxon Motors RE40 DC motors, with 26 : 1 gearbox (see Fig. 3c). In order to feedback the control loop, the motors included 256 ppr encoders to obtain their angular position. Additionally, the

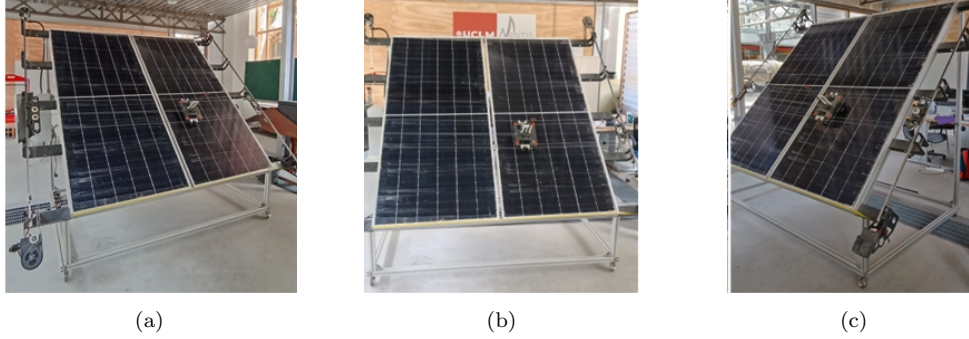


Figure 2: Overview of the prototype

motors are commanded by three servoamplifiers, EPOS2 70/10 controlled via CAN bus through conventional PC connected by a USB port (see Fig. 3b). For illustrative purpose, Figure 3 shows the end-effector, the control cabinet, and one of the driver nodes, including 2 DC-motor sets and guiding pulleys.

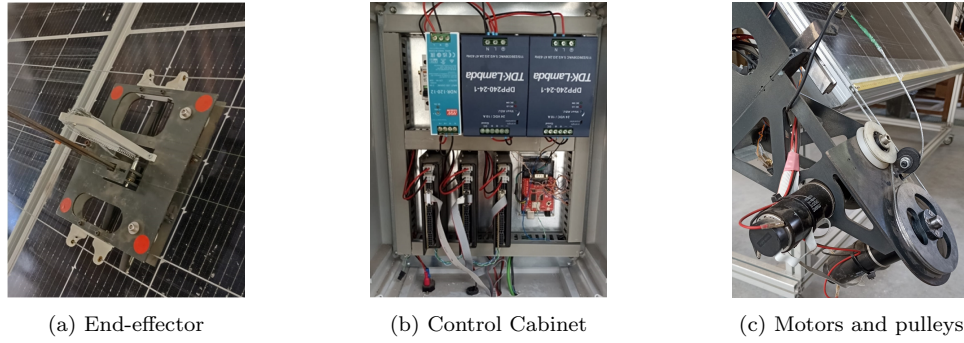


Figure 3: Prototype details

Table x. summarises the main parameters for the prototype.

Additionally, the end-effector is marked with reflective adhesive paper (see Fig. 3a), enabling the measurement and verification of its pose by computer vision techniques. In this sense, the end-effector pose is determined using 1920×1080 resolution camera with 30 frames per second of frame rate (see Fig. 4a). The image processing and data analysis is carried out using the Image Processing Toolbox of the software Matlab®. For illustrative purpose Fig. 4 shows the vision system and one frame of the acquired and treated video to determine the end-effector pose.

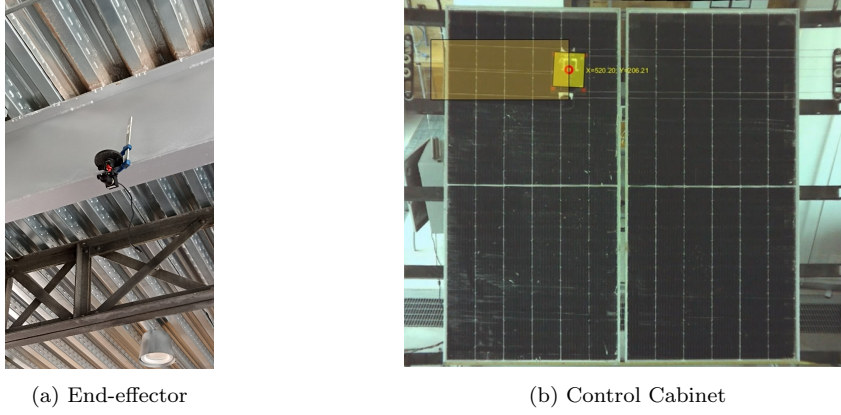


Figure 4: Vision system and acquired frame for end-effector pose estimation

5.2. Simulated Results

Acoplar las simulaciones a la experimentación

This section carries out the validation of the mathematical models proposed. In this sense, the dynamic model of the closed-loop CDPR is implemented using the software Matlab® and Simulink®. The simulated trajectories are 8th order Bezier's trajectories, to ensure smooth trajectories, executed with a fixed sample time of 1 ms while using the ode4 (Runge-Kutta) solver.

The parameters used for simulations are the same ones presented in Table x.

In order to test the reachability of the proposal and its appliance to cleaning solar panels, the following cases of study are executed:

- Case I: Cleaning of one solar panel.
- Case II: Cleaning of both solar panels.

Figures x and x show the trajectory tracking of both cases of study, while Figs. x and x provide the cable tension values throughout the manoeuvre.

It is notable how the trajectory tracking of both trajectories is accurate enough, with an error of xx and xx mm. Additionally, all cable tensions remain within the allowed range, meaning that the proposal is feasible.

5.3. Experimental Results

This section is devoted to show the feasibility of the novel proposal and experimentally validate the results obtained through simulations.

The vision system described on Section 5.1 is able to estimate the end-effector pose over the panels surface within an accuracy of ± 2 mm.

In order to experimentally validate simulations, the cleaning of one and both panels is executed. Figures 5 and Figures 6 show the trajectory tracking by means of this vision system.

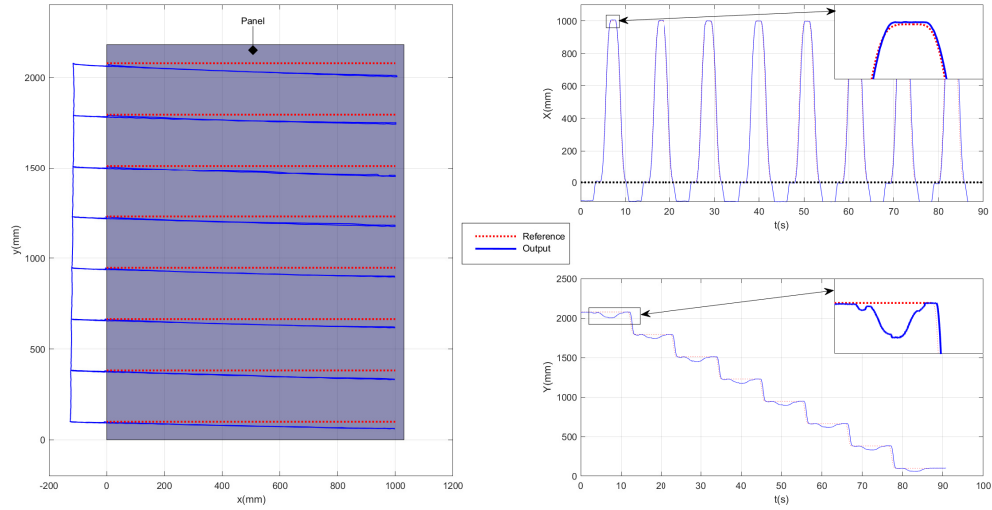


Figure 5: Results for one-panel cleaning procedure

Through the results obtained here, and the measured error of x_x obtained through the computer vision technique and Matlab®[®], we can conclude that the use of this type of CDPR configuration ensures a fine cleaning of the panels.

6. Conclusion

Novel CDPR design with enlarged workspace Fine for cleaning solar panel due to its working area and simplicity of design Kinetostatic model developed and implemented through Matlab and Simulink. Simulations results proves good accuracy and reachability of the proposal. Prototype built to test the real-world application. Results proves that this design works fine for cleaning solar panels thanks to its enlarged workspace.

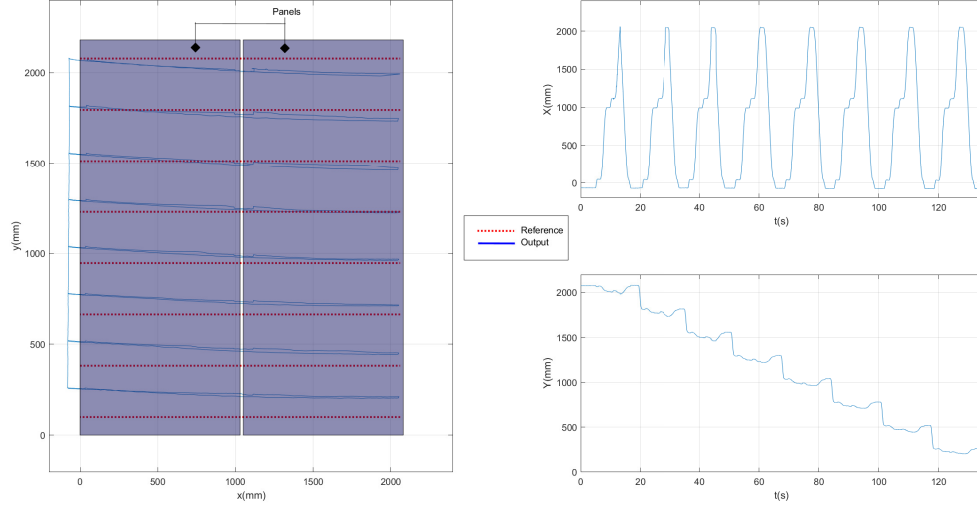


Figure 6: Results for two-panels cleaning procedure

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References

- [1] J.-P. Merlet, Parallel robots, Vol. 128, Springer Science & Business Media, 2006.