Critical Function Prototyping of an Automated Cleaning System for Photovoltaic Panels

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Abstract

Soiling of photovoltaic (PV) panels is a major problem in arid environments like the Middle East. On roofs, where other robotic cleaning solutions cannot be used, a drone-based system could be a flexible and novel solution to this problem. Critical function prototyping is useful when developing such a product service system, by focusing on building and testing the critical component of the system first, instead of using unnecessary resources to prototype the whole system. This paper exemplifies critical function prototyping applied to a drone-based cleaning system, where the cleaning process is considered the critical function. Three prototypes of cleaning modules were built and tested to find the most promising design. The chosen design was then tested to further explore the feasibility of the critical function. Finally, the uncertainties were lowered enough to shift focus towards the integrated system. The use of critical function prototypes in this project enabled rapid testing of multiple solutions without building the whole system, so available resources can be focused where needed.

Keywords: prototyping, early design phase, new product development, cyber physical systems, product-service systems (PSS)

1 Introduction

Drones have emerged as major product and service platforms in recent years with thousands of companies developing new drones and drone-based services. Many such endeavors are extremely resource and time-demanding, with lead times of first prototypes measured in years rather than months. One reason is that companies tend to redevelop entire drones rather than focusing on the critical function specific for their future service offering. This paper focuses on critical function prototyping as key to developing such drone-based services in a fast and agile way.

As a case example, we describe prototyping a cleaning service for photovoltaic (PV) panels. The power output from a PV panel is dependent on the amount of sunlight the PV cells are exposed to. This amount is reduced when the panels become soiled with dirt. In arid environments like the Middle East, PV panel soiling is a widespread problem due to high

amounts of airborne dust and low levels of rainfall (Ferretti, 2019). In these regions, the daily cumulative power loss has been measured ranging from 0.3% and up to 1% (Sayyah et al., 2014). This is a cumulative value meaning that a daily loss of 1% will be almost 10% after ten days if the surface is not cleaned. To limit the power loss, panels must be cleaned frequently.

Over the years, various products have been developed to address this problem. Common cleaning solutions involve using trucks with brushes or robotic systems mounted on panel rows. These solutions can work well on ground installations accessible to vehicles, or where PV panel rows are long enough to justify the investment of one cleaning system per row. However, neither of these conditions hold on industrial-scale roof-mounted PV systems. The constrained space on roofs prevents vehicle access and limits panel row length, preventing the use of efficient cleaning solutions. Therefore roof-mounted PV installations tend to be cleaned by manual labor (Hudedmani et.al, 2017). In areas where soiling levels are high, this can become expensive, reducing cleaning frequency and leading to less power generated from the panels.

For the conditions where the existing solutions with trucks and robotic systems are not feasible, and where manual labor is not feasible, a proposed solution is to use an autonomous drone to clean roof-mounted PV installations. Drone usage is rapidly rising and offers a new dimension of possible applications. A drone provides a flexible platform that could clean non-standard panel layouts, and autonomy could decrease operational cost and increase the frequency of cleaning (Al-Housani et al., 2019; Hassanalian & Abdelkefi, 2017; Liao, 2017). This paper describes the initial development of such a platform, using a method of critical function prototyping.

1.1 Critical Function Prototyping

In this project, we consider a drone-mounted cleaning system as a combination of a product-service system (Baines et al., 2007; Meier et al., 2010) and a cyber-physical system (Baheti & Gill, 2011; Um, 2019) which in recent literature has been labeled as a cyber-physical product-service system (Wiesner & Thoben, 2017; Wiesner et al., 2017) . From now on, it will simply be referred to as the system.

The development of complex new systems can often require decomposing into a combination of subsystems. The concept of a critical function prototype (CFP) involves identifying the essential functional component of a given system, and prototyping solutions to test its feasibility before committing time and resources to other subsystems in the product. The key is to build and test the most ambiguous or uncertain component of a system first, lowering the risk before developing subsequent systems. Insight from a CFP should ideally inform the decision of whether the current design direction is worth pursuing (Lande & Leifer, 2009; Gerstenberg et al., 2015; Elverum et al., 2016; Domingo et al., 2020).

1.2 Aim and Scope

This paper aims to exemplify how critical function prototyping can aid the development of a complex new system. It is presented as a case project of critical function prototyping in the development of a drone-based cleaning system for PV panels. One function of the system, the cleaning process, is identified as the critical function. Prototypes of the cleaning process are built to test underlying principles of cleaning but not to validate a final design. The paper will describe the development of the cleaning subcomponent, as well as learning outcomes concerning critical function prototyping.

2   Development of a Cleaning Module for PV Panels

Multiple concepts were generated at the start of the project provide ideas on how PV panels can be cleaned. These concepts and an early prototype informed the system requirements and led to PV panel cleaning being regarded as the critical function. This is because powerful multipurpose drones for contact operations already exist (DJI, 2020; Trujillo et al., 2019) and they can be precisely positioned using built-in GPS, RTK (real time kinematics), and computer vision systems (Acosta & Toloza, 2012).

In contrast, a cleaning module for this specific purpose is a novel concept and its technical feasibility is not sufficiently understood. It is uncertain whether it can clean well while being light enough and stable enough to be integrated with a drone. This leaves a lot of uncertainty, which can be reduced by building and testing CFPs of cleaning modules. By comparing multiple concepts, the aim is to find the best alternative, as well as variables that affect the cleaning performance. Three concepts will be built and tested based on the criteria given in the next section.

2.1   Evaluation Criteria

The most important factor in evaluating cleaning module concepts is how well the PV panel is cleaned. To test this, prototypes of each concept were built and tested by cleaning a glass plate. The glass has an anti-reflective coating, providing a very similar surface to a PV panel.

A controlled amount of dust was applied to the panel and the amount that remained after cleaning was weighed. The resulting variable is the removed mass. In addition, image processing software is used to identify the total area cleaned. Figure 1 shows an example of a panel that the software labeled as having 67% of its area cleaned, where dust is shown in red.

Figure 1 An example of how the image processing software determines the area cleaned. The red area is dust, while the brown area is clean.

Also, it is important to qualitatively evaluate the evenness of the cleaning result. Uneven cleaning and patterns of dust left on the panels can indicate a method that will struggle to clean PV panels completely, which is undesirable. Finally, to be able to integrate the cleaning module into a drone at a later stage, the stability of the modules was qualitatively evaluated. Good stability allows the drone to fly without being pushed around while cleaning. The level of force that the operator must use to control the module while cleaning determines the stability score. A maximum score of 12 can be awarded based on a score from 1-3 for each of the four criteria. The guidelines for assigning scores are shown in table 1.

Table 1. The four evaluation criteria and point given depending on outcome. From left to right are a) percentage removed dust mass, b) percentage glass area cleaned, c) evenness of dust layer thickness, d) difficulty of control.

Removed mass (a)	Area Cleaned (b)	Evenness (c)	Stability (d)	points
<60%	<20%	Large dust layer thickness variation	Difficult to control with two hands	1
60-85%	20-40%	Medium dust layer thickness variation	Easy to control with two hands	2
> 80%	>40%	Little dust layer thickness variation	Easy to control with one hand	3

2.2 Test Rig

The rig can be seen in figure 2. It consists of two parts. The part to the left is the bottom module that holds a glass surface to be soiled with dust and then cleaned. The part to the right is the top module, which includes a camera and a light source. After cleaning, the top module can be slotted onto the bottom module to photograph the result in a repeatable way.
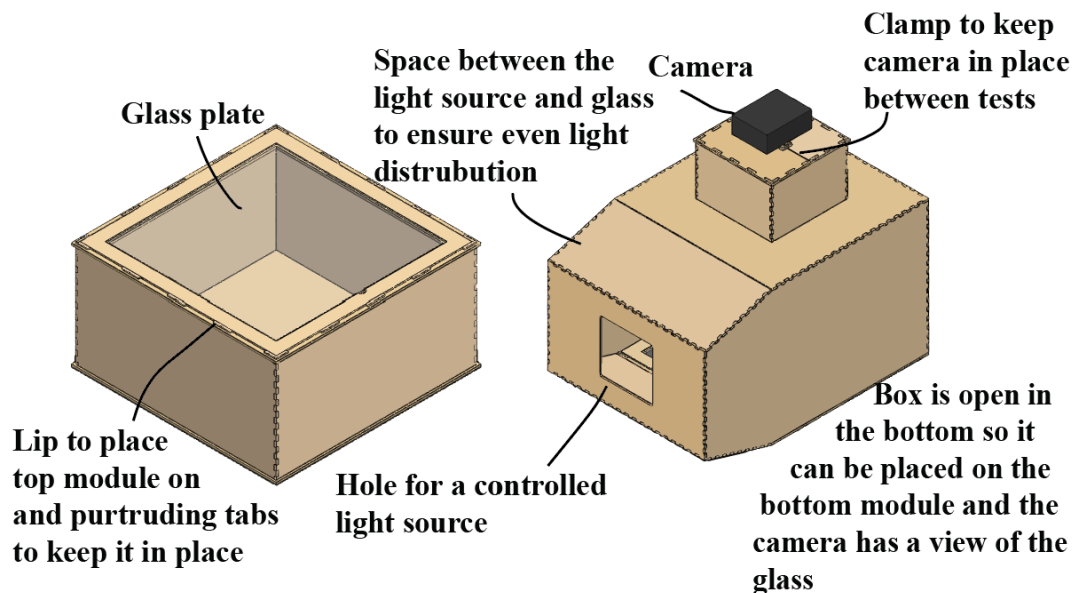
Figure 2 Test rig modules.

2.3 Three Concepts

A CFP only tests the critical subcomponent of the system, which is why quick, handheld prototypes of the cleaning modules were made without integrating them into a drone. This way, the concepts could be tested and evaluated quickly and inexpensively. The three prototypes can be seen in figures 3-5. They were developed primarily through brainstorming with some inspiration from today's cleaning solutions, concept evaluation and a preliminary round of drone-mounted testing of minimum viable prototypes. The concepts allow rotational speed to be varied, brush material to be swapped and the applied pressure altered by adding or removing weights. The Discs concept cleans the panel with two counterrotating flat discs. The Roller concept cleans with a cylindrical brush that rotates against the direction of travel. The Elevated Roller concept is like the Roller but has wheels to create space between the brush core and panel, so only the outer edges of the textile touch the panel.

16 different brushes were made to test the effects that brush material and design would have on the cleaning result. These are shown in figure 6. Most of them were made from a selection of microfiber and cotton textiles designed for cleaning applications.
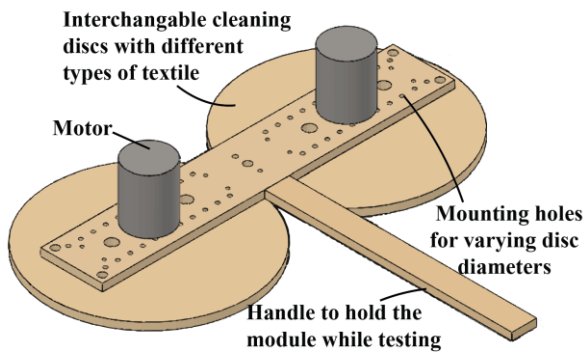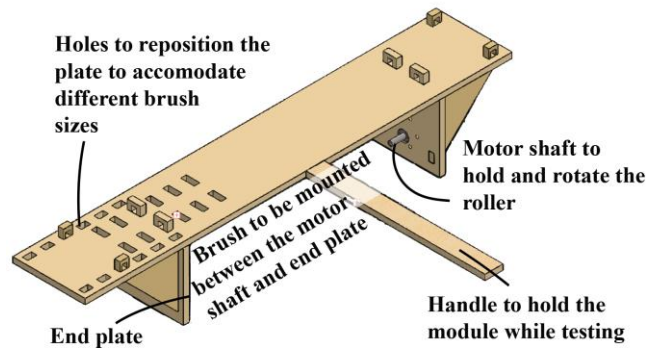

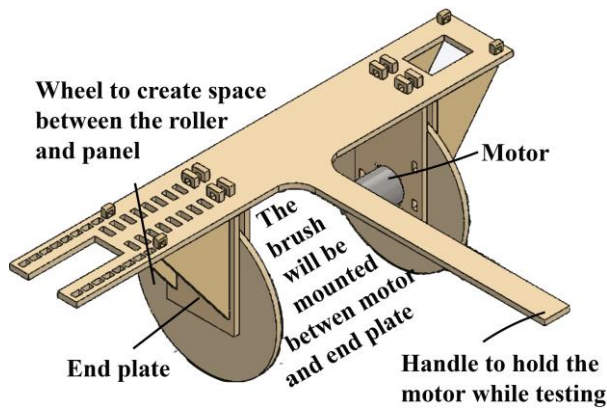**Figure 4 Disc concept.**

Figure 3 Roller concept.

Figure 6 Elevated roller concept.

Figure 5 Brush variations made for the concepts.

2.4 Test Procedure

The purpose of these tests is to find out which of the three concepts, under which conditions, are best at removing dust from a glass plate. The three concepts were therefore tested with different brushes and at varying rotational speeds between 150 and 400 RPM. For the Discs and Roller, the amount of applied pressure was altered between tests. For the Elevated Roller, weight is transferred through the wheels, so brush pressure cannot be altered. However, the size of the wheels was changed to vary the textile overlap. The testing procedure is outlined below.

- Place a clean glass panel in the bottom module.
- Distribute 25g dust evenly on the panel with a sieve.
- Weigh the remaining dust to determine how much has been deposited onto the plate.
- Choose a configuration of concept and brush and set the controlled variables by mounting weights and setting rotational speed.
- Pull the brush over the panel surface at a speed of 0.1 m/s. Hold the concept without affecting the applied pressure. A test can be seen in figure 7.
- Place the top module onto the bottom module, turn on the light, take a picture.

- Set a color threshold for the image evaluation program so an area marked as clean in the program corresponds to a clean area on the panel. Use this threshold for each test.
- Remove the remaining dust off the panel and weigh it.
- Clean the glass plate to prepare it for the next test

2.5   Test Results and Discussion

Figure 8a shows the removed mass percentage for each concept. Elevated Roller removed the most mass on average from the panels and had the lowest variance. The low variance was possibly due to the mechanism of cleaning; Since the brushes used with Elevated Roller hit the panel briefly instead of being smeared across the panel, the brush textiles' affinity to dust should not be an important factor. This contrasts with Discs and Roller where the textile was smeared against the panel and had to trap the dust between textile fibers to remove it from the panel.

Figure 8b shows cleaning results based on the percentage of area cleaned, where Elevated Roller did not achieve as high of a score as Roller and Discs. Although Elevated Roller removed most of the dust, the brush would leave a very thin layer of dust on the panel and limited area would be recognized by the software as "completely clean". This is likely because spots of good cleaning are easier to achieve when pressure is applied like with Discs and Roller.

Figure 8c shows the distribution of total scores for each concept. Due to high scores for removed mass and high scores on the other evaluation criteria; evenness and stability, Elevated Roller received the best overall score.
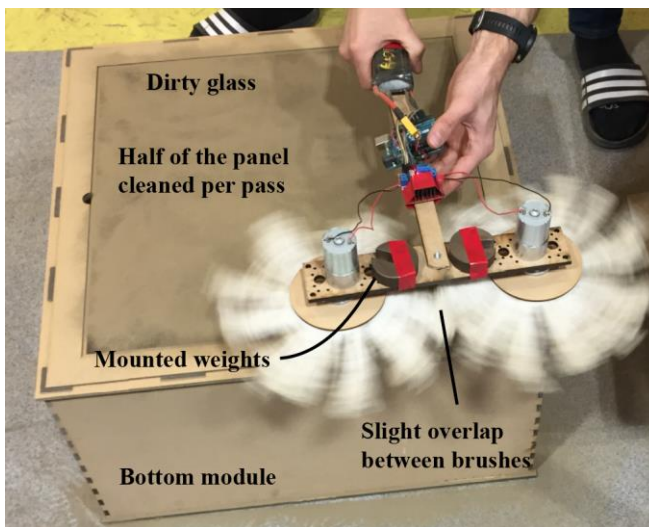

Figure 7 Test being performed with the disc concept.
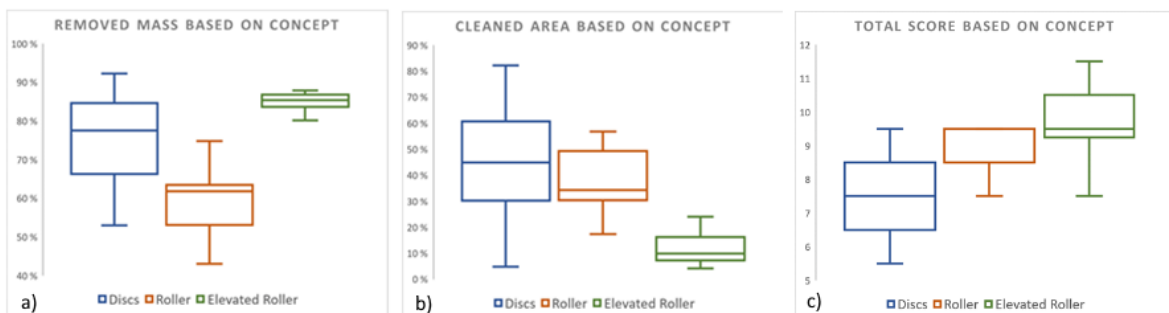

Figure 8 The removed mass percentage (a), percentage of area cleaned (b) for each concept, c) total score of each concept with different brush configuration.

Three brush designs received the same top scores when tested with the Elevated Roller concept. However, two of them showed signs of wear after limited use. The brush which performed best and was the most robust is shown in the lower right of figure 6. The textile was a thin but dense microfiber cloth made from 82% polyester and 18% polyamide. The cloth had been cut into flaps and the edges lined with polyurethane glue to keep the fibers attached during cleaning.

The cleaning results improved with greater brush RPM. However, rotational speed did not have a significant impact on the scores of the concepts relative to each other.

3   Large-Scale Prototype

The previous tests indicate a concept, brush material, and brush design that can be suitable for a cleaning module attached to a drone. However, how the Cleaning Module would behave and clean on a larger scale and the optimal rotational speed was not determined. These factors are important in determining the concept's feasibility on real PV panels. Therefore, a large-scale prototype was built, shown in figure 9.

With batteries and a mounting system, the Cleaning Module weighs 2kg and has a width of 1m. This is within the limits of industrial drones like DJI Matrice 300 RTK, which can hover for about 30 minutes with a payload of 2.7kg (King, 2020). The battery life of the Cleaning Module is also about 30 minutes when cleaning at 750 RPM.

3.1   Test Procedure

A qualitative approach was chosen for these tests. The approach uses real PV panels and visual evaluation of the dust after cleaning. The test procedure is as follows:

- Place two PV panels on the ground and apply the dust.
- Set the cleaner to the desired rotational speed and pass it over the panels at 0.33 m/s.
- Observe how the Cleaning Module acts.
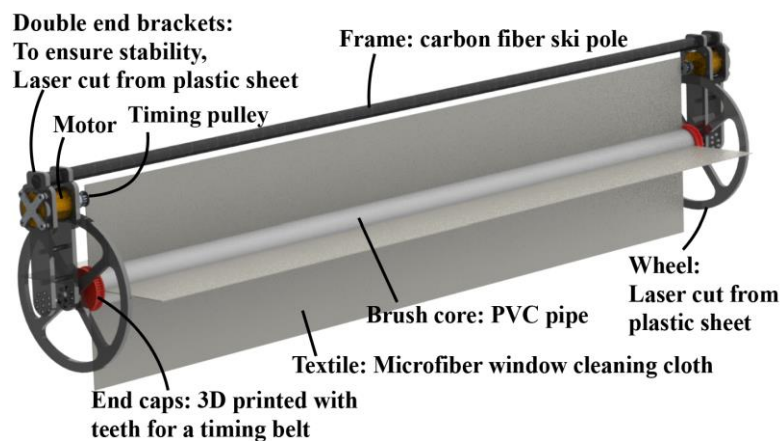- Evaluate the result after cleaning both panels

Figure 9 Render of the large-scale prototype.

3.2   Test Results and Discussion

Although the tests were only visually evaluated, the cleaning results were clearly distinguishable. Two main issues were identified and correlated with rotational speed. In some

tests, we saw the accumulation of dust in mounds. This is shown in figure 10a. The cause of dust mounds seemed to be the brush not exerting enough force to remove dust from the panels. If a drone had been used for the tests, the propeller draft would likely remove excess dust and reduce the occurrence of dust mounds. In all tests, the cleaning module left dust trails, also seen in figure 10a. This seemed to be caused by dust becoming airborne as it was cleaned and redepositing behind the Cleaning Module. Some of this dust will likely be removed by the draft of a drone.
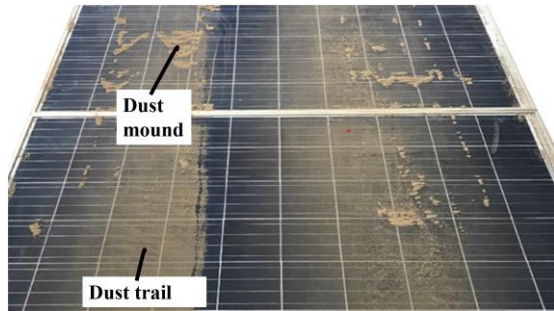

Figure 10a Example of dust mound and dust tails.

Figure 10b Cleaning result at 750 RPM.

The large prototype result improved markedly with increasing rotational speed. The best results were at the maximum rotational speed of 750 RPM shown in figure 10b. At this speed, there were no dust mounds and only weak dust trails. This makes sense because increasing the rotational speed will increase the number of times the brush passes over any given panel area and its force when doing so, thereby removing dust mounds. It also results in an increased airflow which carries cleaned dust off the panel surface, reducing dust trails. Although a higher rotational speed caused better cleaning results the disadvantage is higher power consumption and the possibility that the airflow of the brush can affect the flight characteristics of the drone. Holding the cleaning module or pulling it forward did not require much force. No sudden, powerful movements were created during the cleaning process. However, the module would not move straight, even on a flat panel. This might be caused by differences in friction along the brush width. It could cause stability issues for the drone.

4 Discussion

The first round of tests examined which of three concepts would be most suitable for a drone-mounted cleaning system. A brush that could clean well with this concept was determined. However, it was uncertain how the device would work on a larger scale, on real PV panels, and how the rotational speed would affect the cleaning process. The second round of testing showed that the concept could work on a larger scale and on real PV panels. It also confirmed that the module could provide good results with a sufficiently high rotational speed, transferring only negligible forces to the operator or drone. The design has thus shown the potential to be an efficient cleaning system if integrated with a drone. The pass speed of 0.33m/s was low enough to give good results during testing. A higher speed will make the process faster but may cause diminishing cleaning results. The previous concepts were not tested at 750RPM, but it seems likely that the chosen concept would still perform best, given that the choice of concept was largely independent of rotational speed in the tested range.

4.1 Further Prototyping Work

We divide further work into two categories. The first is testing to get more data for cleaning module optimization. Tests should be performed to get quantitative data on rotational

speed and pass speed, and how they affect the cleaning result and power consumption. Any abrasive effects on the PV panels should also be investigated. During testing, the cleaning results presented dust trails and dust mounds as indicators of poor performance. These phenomena should be measured and eliminated in future tests. The second category is drone integration which concerns how the cleaning module and drone interact. Some work has been done on this previously (Trujillo et al., 2019), but stability tests with an attached Cleaning Module interacting with PV panels, and in outdoor conditions must be performed as well.

5   Conclusion

This paper has shown an example of critical function prototyping used to aid the development of a drone-mounted cleaning system. The cleaning process was determined as the critical function of the system because of its novelty. A better understanding of this process was reached by building multiple CFPs and comparing them. Insight from testing was used to find a design that can work well with the integrated system. The use of CFPs removed the need to integrate each prototype with a drone, which enabled rapid building and testing cycles. These cycles led to an increased understanding of the solution space, which decreased risk without having to build the whole system each time. Now an integrated prototype can be built to test the remaining uncertainties.

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