# Towards the Next Generation of Multi-Robot Systems for Solar Power Plants Inspection and Maintenance

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***Abstract***

**Solar panels cleaning has always been a key task in solar power plants inspection and maintenance, being directly related with the overall performance of the system. A wide range of cleaning setups, tools and machines have been tested and commercialized over the years, most of them being manual or semi-autonomous, and usually dedicated to only one photovoltaic module bank. This need has been further emphasized with the ever-growing installation of large utility scale solar plants in desert regions. This short position paper introduces a fully autonomous, battery powered, multi-robot system designed for infrastructure inspection and maintenance of large solar power plants, thus drastically reducing the costs needed for those services up to now. The heterogeneous system includes both unmanned ground and aerial vehicles, fully integrated within the same architecture. Despite being a work-in-progress, the experimental results demonstrate the performance of the multi-robot system, addressing the decision-making as a sequence modeling problem.**

## I. INTRODUCTION

Globally, a total capacity of about 1 TW of solar installations has been already installed and a large growth is foreseen for the upcoming years, with an addition of 120 GW expected in the large-scale photovoltaic (PV) sector (utility-scale PV). With an average installed capacity of 200 Wp/m², this corresponds to an increase in PV area of, at least, 600 km² / per year that needs to be cleaned and monitored about possible defects. Arid areas, like the Middle East and North Africa (MENA) regions, are heavily affected by sandstorm pollution, while, according to the International Energy Agency (IEA) Renewable Energy Market Update of May 2022, the MENA region alone is expected to add 10 GW of PV in 2022 and 2023 [1]. This pollution-affected areas require cleaning services to be provided several times a year. However, based on individual outstanding PV plants, such as the 2.2 GW PV plant (11 km²) in the desert in China's remote Qinghai province, there is a massive need for regular cleaning [2]. Therefore, within the large-scale plant segment, we conservatively assume that there is, at least, a global increase of 50 km²/year in the area to be regularly cleaned and inspected. Given the size of these installations and the current needs, a necessity emerges for more efficient and autonomous systems to be deployed [3].

This short position paper briefly describes the use of a multi-robot system (MRS) capable of working, collaborating, and allocating tasks autonomously to each other, to provide inspection and cleaning (I&C) services to multiple PV solar banks. A sophisticated coordinating architecture is described to deal both with the task allocation along the fleet and the decision-making process, which is not only usually affected by local weather and soiling conditions, but also the cleaning strategy adopted.

## II. SPARC I&M: MRS FOR SOLAR PANELS I&M

### *A. Robotic platforms*

SPARC I&M Robotic Innovation Experiment involves the coordination of four different robotic platforms, both unmanned ground robots (UGV) and unmanned aerial robots (UAV), in a complementary way to cover a large range of maintenance challenges, including the regular cleaning and inspection for defects on utility scale solar plants located in remote areas. These four platforms include (Fig. 1): (i) F1A: a lightweight UGV, flexible to clean any solar panel layout and navigate on PV banks with inclinations up to 25 degrees [4]; (ii) R1A: a lightweight UGV, designed to clean single-row PV banks and to deliver the expected result even in steep inclinations; (iii) T1A: a heavy-duty track UGV designed to transfer F1A and R1A UGVs between different PV solar banks and their base station; (iv) U1A: UAV for detecting and identifying possible defects on solar panels surfaces.

In a nutshell, F1A and R1A belong to the same category as cleaning robots, i.e., robots designed to clean solar panels. The T1A is a supportive agent, often categorized as "mother" robot within the marsupial robotics domain [5], as it has been designed to transport cleaning robots in-between different solar panels, and back and forth to the base station for charging.

All robots are fully integrated in the Robot Operating System (ROS) framework [6], include a wide range of sensors for pervasive localization and safe operation, such as inertial Measurement Unit (IMU) and Global Navigation Satellite System (GNSS) with Real-Time Kinematics (RTK) corrections for all robots, depth camera and 3D light detection and ranging (LiDAR), and high-resolution thermal camera for the U1A. Robots' decision-making runs locally on every agent by adopting a behavior framework to manage complex behaviors using finite-state machines (FMS) [7]. Nonetheless, the system comprises a central coordinator that provides high-level goals for coordination purposes, which is a central component of the MRS architecture.

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**Fig. 1.** System architecture of the MRS for solar panel I&M. top left) F1A; top right) R1A; bottom left) T1A; bottom right) U1A.

*B. MRS Architecture*

A sophisticated Fleet Management System (FMS) has been developed, which integrates, monitors and coordinates robots to meet the established goals (Fig. 2). The coordinator integrates a Nakama-ROS server, which communicates with a Unity3D User Interface (UI) client, ensuring safe machine-to-machine connection between robots and clients.

Since SPARC I&M adopts ROS, all the high-end sensors are easily integrable for further options in the inspection domain. Furthermore, as a cooperative robotic system integrated within an IoT infrastructure, the optimal cleaning strategy is guaranteed by having a Nakama-ROS server to autonomously manage fleets of robots. It is noteworthy that Nakama has been solely used before as a game server engine. In this work, we have adopted Nakama not only to manage multiple users and sessions, but also to be the central coordinator of the MRS. This has been possible by implementing an extension to Nakama server, which additionally offers full low-level access to the server and its environment.

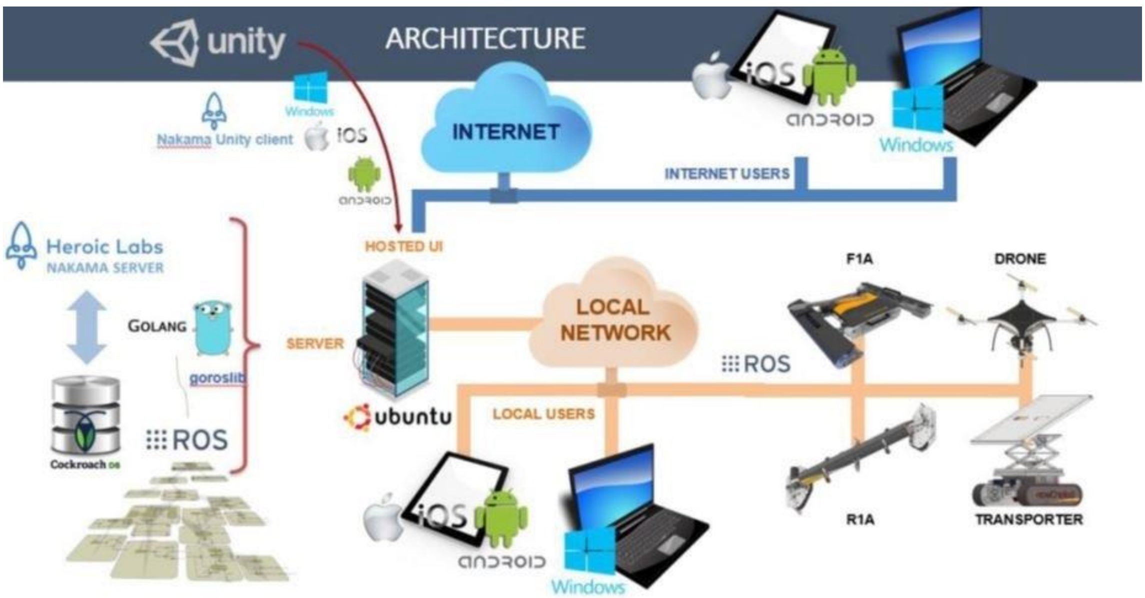


**Fig. 2.** System architecture of the MRS for solar panel I&M.

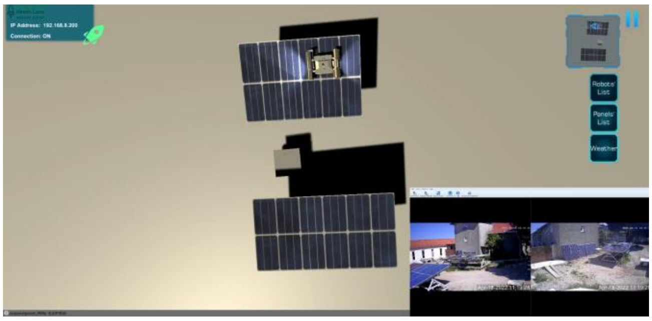

**Fig. 3.** UI of the MRS for solar panel I&M.

The UI, as previously stated, has been developed using the Unity3D framework (Fig. 3). Even though Unity3D has been mostly used to developed videogames and apps, it has been widely used in mobile robotics in the design of user interfaces for human-robot interaction (HRI) [8]. The key advantages fall on the assets available to design easy-to-use graphical UI for animating objects and controlling interaction, the ability to communicate with external hardware, the ability to process multimedia sensory data, and the ability to offer support for multiple operating systems (cross-compatibility).

When it comes to the introduction of new decision-making into the robot, we have once more adopted the behavior engine. In the central coordinator, however, behaviors are triggered by the Linux OS CRON job scheduler. This allows keeping the overall coordination easily maintainable and extendable. This means that, whenever a new behavior is required, it can be implemented as a single state of the FSM, or "broken" into smaller states, keeping it as generic as possible and reusable.

## III. EXPERIMENTAL RESULTS

The experimental layout was chosen to encompass a large range of panel tilting, so as to create challenging conditions in which the system would have to respond in a safe way.

A sequence of actions is shown in Fig. 4, which contemplates the execution of the cleaning service by a F1A (action 1), its completion and coordination through the FMS to move the F1A and T1A to a rendezvous predefined position (action 2), the successful pick-up of the F1A (action 3), and, at least, the transfer to the charging station (action 4). In parallel, the UAV performs a series of predefined flight routes for defect detection.

This sequence of actions was carried out on a repetitive basis to quantitively assess the performance of the system. It is noteworthy, however, both deployment of the F1A on top of the panel using the T1A was not considered in these tests. This was not foreseen at this stage since the localization estimation of the F1A degrades over time while deployed on top of the moving T1A. This occurs as the Extended Kalman Filter (EKF) is used to integrate odometry estimation from GNSS, IMU and wheel odometry, which tends to diverge in the presence of motion caused by another platform (i.e. the T1A). This is a recognized problem that will be tackled in a next iteration. Therefore, after the T1A picks the F1A from the solar panels, the F1A has been manually deployed again on them, repeating the whole experiment afterwards.

**Fig. 4.** Sequence of actions perfomed by the MRS and coordinated by the FMS.

Data obtained from weather stations [9] and soiling measurement sensors [10], taken into account in the decision-making process, while an alarm system was able to monitor and report possible malfunctions.

50 trials were performed for each inclination of the panels, varying between 0 and 25 degrees, with 5-degrees steps, leading to the results illustrated in Fig. 5. Data was acquired both from datasets generated by robots (i.e. rosbags) as well as cameras available on-site. The execution of a given phase was considered successful when performed without any number of retries, even though the individual behavior of robots contemplated a series of recovery behaviors to ensure the completeness of the overall sequence of actions. The area

graphs presented in Fig. 5 represent the phases of the sequence (x-axis), the different tilting conditions (y-axis) and the performance of the system (z-axis).

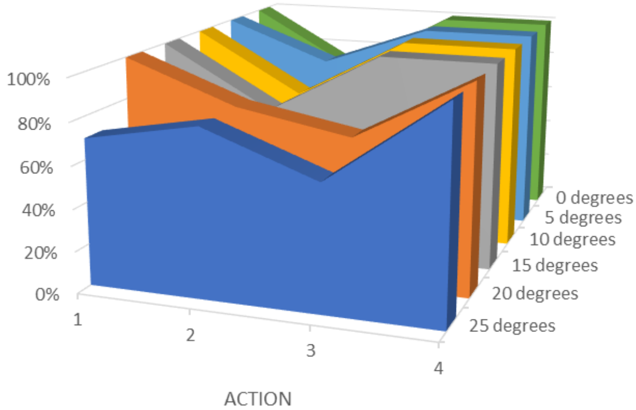


**Fig. 5.** Results retrieved from the 50 trials performed.

The experimental tests focused more on the most challenging conditions for the F1A-T1A dyad and how efficiently they could deliver I&M services under the multi agent command, given the high degree of complexity inherent to their collaboration.

From these tests, one can withdraw the following conclusions:

- Action 1: The F1A presents a high-level of reliability during cleaning for inclinations up to 20 degrees (100% successful). For 25 degrees, however, the cleaning tests were not always successful as the F1A robot would slide, thus being successful only 70% of the time.
- Action 2: The T1A can successfully park 80% of the time, regardless on the panel inclination. In several occasions, the T1A had to repeat the whole parking process to correct for positional and orientation deviations from the solar panel.
- Action 3: The F1A is capable of docking on the T1A with a high-level of reliability up to 15 degrees (100% successful). Again, the sliding of the F1A made the docking on the T1A challenging. For 20 and 25 degrees inclinations, the F1A required more than one attempts to successfully dock in the T1A, thus dampening its success to 70% and 60%, respectively.
- The return to base by the T1A with the F1A on top was always successful and independent from the panel inclination (100% successful).

## IV. Conclusion

This short position paper intends to demonstrate a novel MRS architecture that contemplates a heterogeneous team of robots for I&M in large utility scale solar plants. While it is still a work-in-progress architecture, the overall system is robust and presents promising results, with current pilots being established in Saudi Arabia and Dubai. Furthermore, the tools adopted provide a high-degree of flexibility and extendibility, using FSM as main computation model to manage complex behaviors, as well as game-based engines, such as Unity3D and Nakama, to manage HRI in a user-friendly manner.

Further improvements on the decision-making side for cooperative cleaning are foreseen as future work. Furthermore, more tests in real life conditions are also needed in installations with harsh environmental conditions to stretch the system and detect possible sources of failure.

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