Demonstration of Laser Power Delivery for Mobile Microrobots

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ABSTRACT

Advances in autonomous robotic networks have allowed for many applications in communication, exploration, and monitoring. However, a major limitation in developing truly autonomous systems with robots is its operation time, often bottlenecked by the mismatch between battery capacity and power demands for motion. This challenge is especially challenging for miniature or microrobots given the limited payload they can shoulder. To combat these shortcomings, we demonstrate an integrated laser power delivery system that tracks and steers ground robots that will be capable of delivering a sufficient amount of power that could support motion, communication, and sensing. Our results independently demonstrate sufficient power delivery from the optical circuit and promising tracking error with our event camera tracking pipeline. However, the integrated system reveals future challenges in realizing a fully integrated power delivery system.

CCS CONCEPTS

• Computer systems organization → Robotics; **• Hardware → Energy distribution**; *Emerging optical and photonic technologies.*

ACM Reference Format:

Charles J. Carver[1], Toma Itagaki[1], Kechen Liu[1], Megan G. N. Manik[2], Zachary Englhardt[3],, Vikram Iyer[3], and Xia Zhou[1] . 2024. Demonstration of Laser Power Delivery for Mobile Microrobots. In *The 10th Workshop on Micro Aerial Vehicle Networks, Systems, and Applications (DroNet' 24), June 3–7, 2024, Minato-ku, Tokyo, Japan.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3661810.3663466

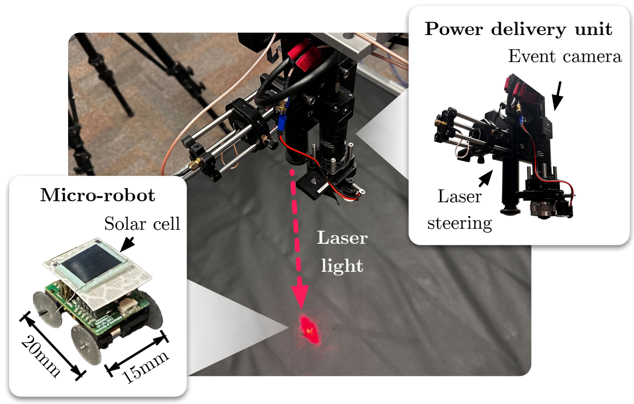

Figure 1: Laser power delivery system — composed of an event camera and laser steering optical circuit — wirelessly transmitting energy to a miniature robot.

1 INTRODUCTION

Continuous monitoring of an area using stationary sensor nodes is a tedious and costly task considering the overhead of charging and maintaining each sensor. An example of a challenging task is sensing the environment to measure the impact of climate change. Autonomous robot deployments are widely considered the gold standard for conducting such exploration, as they have the capability of wide-scale sensing without requiring human intervention. However, these mobile robots rely on limited battery capacities which necessitates short excursions before returning to a central location for charging. Furthermore, the next generation of *bio-inspired robots* — those that leverage designs found in nature for efficient locomotion — are even more constrained by the inefficiency of current battery chemistry compared to the energy per unit mass of natural energy sources of biological insects such as carbohydrates or fats. Simply increasing the battery capacities is equally intractable, as the added weight would exceed the payload capacities of the various platforms (e.g., bio-inspired aerial drones [1], which can only support 100s of milligrams of weight). Taken together, these barriers prohibit the wide-scale deployment of autonomous robots for ubiquitous environmental sensing, as they necessitate a dense deployment of charging locations for any meaningful applications.

Instead, we demonstrate a wireless optical power transfer system for delivery of power to a mobile target. The idea of wireless optical power transfer to drones has been discussed and analytically explored [2–4] and implemented in a few systems. At the miniature scale, two works have demonstrated the untethered flight of insect-sized robots, albeit with flight durations restricted to mere seconds after takeoff [5, 6]. Aerial drones require hundreds of volts to power their mechanical actuators that drive wings and motors [1, 6], which presents multiple challenges beyond wireless tethering such as boosting the harvested energy and issues with heat. However, on the ground drones present an application with less rigorous power requirements.

In ground drones, a more common approach to combat the discrepancy between power supply and demand is to carefully design the specifications to meet the power supply. For example, the MilliMobile is a battery-free system that implements low voltage (less than 10V) vibration motors powered by small capacitors [7]. Furthermore, an insect-sized rolling microrobot was powered with either a laser or a supercapacitor [8]. The device is motorized with a low-voltage (1-3V) electromagnetic actuator, allowing for a short

DroNet' 24, June 3–7, 2024, Minato-ku, Tokyo, Japan

ACM ISBN 979-8-4007-0656-1/24/06…$15.00
https://doi.org/10.1145/3661810.3663466

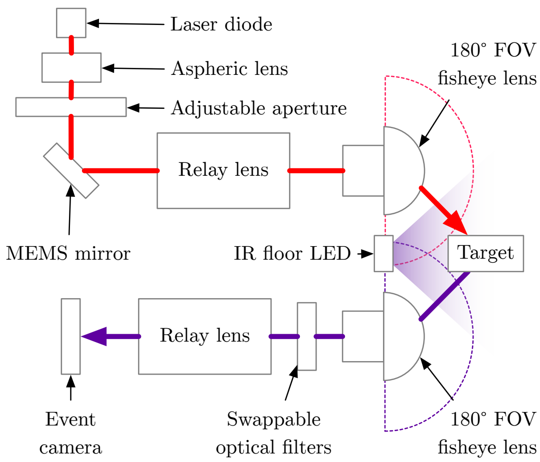

Figure 2: Integrated optical circuit for delivering laser power, illuminating the scene with IR light for sensing, and tracking via an event camera.

period of self-sufficient motion. However, with the laser-powered design, the microrobot faces the challenge of accurate and continuous laser delivery.

The central goal of this paper is to report initial findings and foreseeable challenges for future work in developing a closed-loop integrated power delivery system. While the current system does not demonstrate novel designs or algorithms with regard to laser power delivery and tracking, we contribute the first integrated system with laser power delivery to mobile targets. Unlike [9] — which proposes a generic framework for maintaining laser connectivity with mobile targets — we explicitly focus on evaluating the practicality of *power delivery* using a modified optical circuit and event camera tracking design. The current design is preliminary work to power ground robots such as the [7] which we believe will support future systems that power multi-robot systems and aerial drones. Our main contributions include:

- An initial implementation of an integrated laser power delivery system utilizing a steerable MEMS mirror and an event camera.
- Evaluation of the delivered power to a mobile target.
- Analysis of the tracking and power delivery components.
- Discussion regarding ongoing work of laser power delivery.

2 DESIGN

We present a basic system design of laser power delivery to a single mobile target drawing inspiration from the designs of LaserTag [9] and AmphiLight [10]. The design consists of the optical transmission circuit, event-based tracking system, and power receiver.

Optical Tracking. For tracking, our design implements an event camera for lower latency tracking of mobile targets. Event cameras are a relatively new family of image sensors that are inspired by the neural mechanisms of the retina; instead of capturing the per-pixel color and intensity, event cameras return an asynchronous stream of changes in pixel intensities [11]. This unique image-sensing provides a multitude of advantages over traditional image frame cameras, such as high temporal resolution, low latency, low power, and high dynamic range. Again, when considering the design from prior works [9], the RGB camera posed two limitations — lower latency and smaller targets. Since the targets we consider are microrobots on the scale of tens of millimeters in length and width [7], requiring precise tracking with little to no payload available. We utilize the low latency of the event stream to provide high-speed tracking of mobile targets using a lightweight clustering algorithm [12]. The biases (or event camera settings) are carefully tuned to our current laser wavelength and additional infrared transmitter described below.

Integration. The design of our system is inspired heavily by [10] and [9], including the steerable MEMS mirror and fisheye lens. However, for the optical transmission to scale to higher power throughput, the incumbent design [9] faces challenges including loss of power from optical components such as the beamsplitter and damage to optical components such as the fisheye lens at high laser powers. Instead, the current design exploits the fact that the current applications of robots are only mobile on a single ground plane, allowing for the system to not be colocated — the camera and laser transmitter's pinhole locations are not in the same trajectory which allowed [9] to omit depth information when steering. As a result, the system requires an initial mapping between the laser steering angle and tracking output coordinates.

Without depth information and colocated tracking and steering, there is an additional necessary step to control the MEMS mirror to the tracked target within the event stream. The system requires a one-time mapping phase where a laser is shone on the ground in a known pattern using the MEMS mirror to steer the laser. The laser patterns are tracked in the event stream to create the mapping between tracking output coordinates and the steering angle.

Receiver Design. In addition to supporting power delivery, the robot target must be trackable via the event camera. The preferred method is a purely computer vision-based approach that requires minimal modifications to the robotic platform. This is especially important for micro-robotics which have limited payload and which should be prioritized for onboard sensing and communication capabilities. However, computer vision-based approaches are prone to noise and ambiguity because of the lack of information in event streams compared to RGB cameras. Alternatively, the unique characteristics of the event stream can be leveraged to create a very robust stream of events by augmenting the robotic target with retroreflective markers on the robot [9]. While this adds payload and may not be a feasible option for all applications, the biases on the event camera can be tuned to filter out signals that are not coming from the retroreflector using an LED transmitter at a certain frequency or bandwidth.

To reduce false positives in the event stream, we are considering a dual-bias approach. With neuromorphic cameras, a single event is triggered if the incident light onto a pixel is above a certain bias threshold. To limit false positives in the event stream, we can tune the bias to isolate our robotic target. If the target is equipped with an active or passive luminary — including ones modulated at known frequencies — the bias can be further tuned to isolate the receiver. However, we also desire to see the peripheral event stream to automatically disconnect laser power in the case of link occlusion. For our power delivery experiment (further discussed below), we leverage retroreflective markers underneath the photovoltaic cell to create a recognizable and trackable signature, whilst filtering out the events created by the motion of the vacuum robot and additional power measurement circuitry. The transmission setup is augmented with an infrared LED transmitter to enhance the reflected light off the retroreflective marker.

To harvest the majority of laser light, we must utilize a high-efficiency photovoltaic receiver. Common photovoltaics have an efficiency around 20% to 30% and are designed for broadband optical sources (e.g., the sun). By leveraging laser light, we can consider photovoltaic cells with 40% conversion efficiency between 900 nm and 1000 nm. This efficiency is possible with Si-based vertical multi-junction PV cells which have a V_{OC} voltage between 3 V and 30 V with corresponding I_{SC} between 5 mA and 20 mA.

3 PROTOTYPE IMPLEMENTATION

To deliver laser power to our moving target, we implement an integrated laser tracking-steering prototype using off-the-shelf components. The high-level rationale of our system is we (a) map each image sensor pixel to a corresponding laser angle, (b) obtain the pixel coordinates of real-time events, and (c) use our mapping to compute the corresponding laser angles.

3.1 Hardware Overview

To deliver laser energy to the receiver, we first leverage the basic optical design of [10]. Specifically, we utilize an $f \approx$ 3mm aspheric lens to focus a 150mW, 638nm laser diode (L638P150) onto a Ø3mm goal-coated MEMS mirror. The MEMS mirror utilizes a high-voltage, bipolar drive signal which is controlled digitally via a USB interface provided by the manufacturer. The reflected light then passes through a Thorlabs MAP10 achromatic relay lens before exiting a 180° fisheye lens. The optical elements are arranged to produce a roughly 2° full-angle diverging beam. Energy densities of the transmitted laser light measured 1 m from the steering unit are on the order of 10s of mW/cm^2.

To track objects, we leverage the Prophesee's EVK4HD in our prototype, which houses Sony's IMX636 [13]; the higher 1280x720 pixel resolution was attractive given the small size of the MilliMobile. Notably, we require a method for differentiating between the steered laser light in the scene and the moving target, or else the projected laser light may be locked onto during tracking. Consequently, we enable wavelength filtering of the scene during mapping and tracking by leveraging a sliding filter (Thorlabs CFS1) containing an infrared (IR) high-pass and low-pass filter. In this way, we may create our mapping using the IR low-pass filter (thereby enabling the camera to see the 638nm laser light), and perform tracking using the IR high-pass filter (which blocks all visible light from reaching the event camera). To introduce sufficient amounts of IR light into the scene, we colocate an 850nm, 150° LED with the camera. Furthermore, to correct for the mismatch between imaging focal length (determined by the 180° fisheye lens used for imaging) and the extra space needed for the filtering, we add a Thorlabs MAP10 achromatic relay lens between our filter and image sensor.

3.2 Mapping and Tracking

To perform target detection and tracking, we utilize Prophesee's Metavision SDK which includes prewritten modules to handle the event stream, processing, and tracking of objects [14]. Specifically, we process at a rate of 120Hz, with an event accumulation time of 50000 μs. The tracking algorithm is implemented using a modified medoid-shift algorithm [12].

During the mapping phase, we steer the laser light onto our ground plane ($\approx$ 1m from the core unit) into an evenly spaced grid covering a 2m $\times$ 2m square area. Our event camera tracking algorithm obtains the center pixel of the projected laser light at each point in the grid and records the corresponding MEMS voltage needed to reach that location. Since the mapping grid cannot cover all potential pixels on the image sensor, we instead leverage the mapping technique of [9] and fit two 2D surfaces for each MEMS drive voltage. Once we have obtained the coefficients for our mapping surfaces, we then leverage them to obtain the corresponding drive voltages for any target location recorded by the event stream.

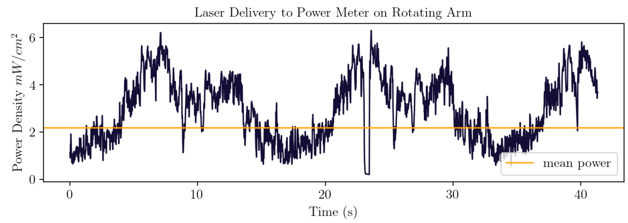

Figure 3: Power meter readings from laser delivery experiment on rotating arm at 22° per second

3.3 MilliMobile

Our system design is tuned for an insect-sized robot, MilliMobile, which can be powered by solar cells and operates at a minimum power of 50μW [7]. The size of the robot measures 20mm by 15mm with a height of 12 mm and weighs 2.96 g. Furthermore, the onboard circuitry supports communication via Bluetooth and can support a 3g payload of analog and digital onboard sensors to autonomously move based on environmental values. While we do not directly power the robot, instead, to demonstrate the feasibility of powering the robot, we mount a photovoltaic (PV) cell atop the MilliMobile and measure the power delivered while the robot and power meter system are mounted on a moving arm.

4 EVALUATION

To demonstrate the feasibility of mobile power delivery, we measure the optical power delivered to a power meter measuring density mounted on a rotating servo arm, moving at 22° per second as a simple model of a moving microrobot. We follow the steps outlined in the design to map pixel coordinates to laser steering angle, then run the tracking algorithm to track and deliver power in real time. The laser implemented in the evaluation is a red 638nm laser with 675mW of electrical power and sits 1.1m above the ground. The experimental results, namely the power density values over time are shown in Figure 3. The results show periodic a pattern within the power density that aligns with the angular velocity indicating that the steering is uneven in different parts of the circular path. We expect to see a flat line at the highest power density with perfect tracking and steering. Nonetheless, the power density does not drop to zero, showing that with our current system, some proportion of the laser is always covering the target. We anticipate these issues

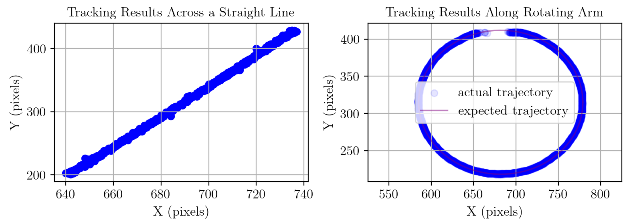

Figure 4: Tracking stability results for translational motion (left) and circular motion (right).

to be solved with improvements to the mapping step or unknown ambiguity caused by the optical circuitry.

4.1 Micro Benchmarks

In this section, we report micro-benchmarks on tracking and power delivery independently.

Tracking Stability. First, to demonstrate the stability of event-based tracking on a known trajectory, the same 10mm x 10mm PV cell is mounted on a platform that can move directly along a metal railing. The estimated X and Y pixel coordinates are reported on the left of Figure 4. Although we do not have a ground truth value, we evaluate the tracking output against linear regression which yields an r^2 value of 0.999 and p-value < 0.001. Furthermore, the root-mean-square error is 1.822 pixels, which is roughly 9.75 mm when converted to mm.

Secondly, we demonstrate that the periodicity of the laser power delivery results from above are not due to tracking errors, but rather from unknown issues with the optical circuit and/or the pixel coordinate to steering angle mapping. We use the same experimental setup to validate whether the tracking output coordinates are similar to the expected trajectory given a known angular velocity of 22 °/s that the arm is moving at, and a constant radius of 25 cm that the arm is being mounted to. The X and Y coordinates are shown in Figure 4. The gap at the top of the figure likely occurs due to the IR transmitter LED placed along the line of the trajectory. It is important to note that this lack of tracking output does not correspond to the dips in power delivered in Figure 3.

Laser Power Harvesting. Lastly, we demonstrate the power delivery in a testbed with a 976nm laser shining directly onto stationary photovoltaic cells to measure the achievable power delivery. The 10W laser is provided with variable electrical input power, which is delivered directly to the photovoltaic cell. The load is varied during the experiment to measure an I-V curve which is used to estimate a knee point corresponding to the maximum power point. The converted voltage and current values are reported in Figure 5. Both PV cells are from MHGo Power — the 3mm x 3mm PV cell has a V_{OC} of 9.8V, I_{SC} of 5.2mA, maximum power of 45mW at a 40% efficiency while the 10mm x 10mm PV cell has a V_{OC} of 32V, I_{SC} of 20mA, maximum power of 533mW at a 40% efficiency. The measured knee points and the reported knee point follow the expected trend for both the 3mm x 3mm and 10mm x 10mm PV cells with just under 40% efficiency.

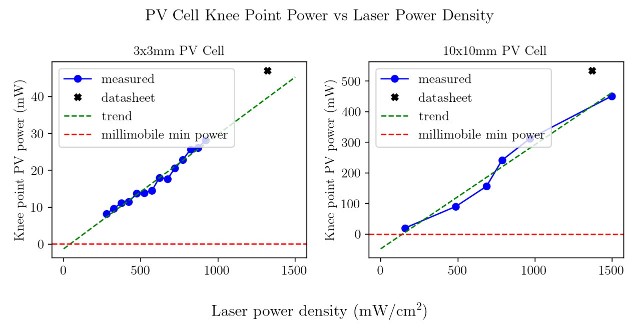

Figure 5: Maximum power delivered through two photovoltaic cells at varying laser power densities. The laser used was a 10 W, fiber-coupled 976 nm laser placed ≈10 cm away from the photovoltaic cells.

5 DISCUSSION AND ONGOING WORK

The current work reports preliminary results of an integrated power delivery system to mobile targets. While the overall power delivery results showed incomplete power delivery, the micro-benchmarks performed independently with respect to the tracking and power delivery components show promising results for future work.

Laser Steering. The current system is limited to laser steering in a single plane (i.e. ground robots on a single surface). The mapping mechanism assumes that all targets are co-planar given the lack of depth information from the monocular event stream. There are further methods to improve the tracking to include depth information for more robust applications with methods that use 2D-pixel positions of known features to translate into a 6-degree-of-freedom output using methods such as perspective-n-points. Alternatively, many works utilize stereo vision setups to capture depth information. Furthermore, the mapping mechanism is performed using the laser signature on the ground, while the tracked object — whether it be the PV cell atop a MilliMobile or the rotating arm — inherently adds height from the ground, causing a discrepancy between the initial mapping and the intended target. Moreover, the current design separates the laser from the tracking system (in other words, they are not co-located) which introduces depth-ambiguity requiring the mapping stage. Instead, a co-located design could be reconsidered, however, the co-location comes with limitations in the optical power that can be throughput.

Heat and Safety. The microbenchmark of the PV cells shows potential for power delivery in the hundreds of milliWatts. The high power throughput may be sufficient to drive aerial actuators requiring high voltage, but there are further challenges that we foresee such as the stricter payload with aerial drones conflicting with components required to handle increasing heat with such high optical power. Furthermore, the wavelength that these high-efficiency PV cells are tuned to is 976nm. When driven with high power density, the laser can be dangerous when illuminating human skin and eyes. To ensure the safety of such a system, the event camera stream can be reused as a high-speed safety mechanism that shuts off the laser when unknown objects enter the proximity of the laser.

Multi-Robot Systems. While supporting a single target remains a challenge with our system, we foresee further benefits of laser power delivery in multi-robot systems such as with multiple MilliMobiles [7]. The applications with multi-robot systems span many domains including environmental monitoring, source localization, and simultaneous localization and mapping (SLAM). However, given the limited computing power and energy capacity of each robot, a multi-robot system operates with limited control onboard and instead is controlled via off-board computation. Multiple robotic units, each equipped with sensors, can create a sensor network, and the mobility of each robot improves coverage via dynamic reconfiguration of the robotic network. Furthermore, the autonomous nature of robotic systems can be used to replace humans in applications that pose health threats such as gas source localization [15] and forest fire source location [16] and applications that require extended time such as searching warehouses [16]. A foreseeable challenge in developing a closed-loop integrated power delivery for multi-robot systems is in achieving efficient power multiplexing using a single laser source.

6 RELATED WORK

Wireless Power Delivery. To address the issue of battery limitations in drones, wireless power delivery has been explored in recent years for remote applications using multiple energy sources. The appeal of wireless power lies in its ability to transmit energy without cumbersome cables, preserving the mobility of the system and potentially enabling uninterrupted operation on the go. For instance, recent studies have explored the use of magnetic resonance technology to wirelessly charge unmanned aerial vehicles (UAVs), as demonstrated in [17], achieving a power delivery of 5W. Additionally, the research highlighted in [18] showcases the potential of RF harvesting to deliver sub-watt power. Recent works have also investigated wireless power delivery in the context of autonomous drones [2, 19].

In this work, we are focused on optical wireless power delivery, which uses light waves to deliver power wirelessly. In general, laser-based wireless power delivery for drones can be split into two categories; the first being systems that charge a battery [20, 21]; the second being systems that convert the laser power directly into actuating force [1]. Several systems have been implemented to wirelessly power aerial drones, tracing back to pioneering efforts by NASA with their MOTH1 and MOTH2 systems [22]. In 2011, a commercial company demonstrated drone hovering for 12 hours [23] with low (10%) conversion efficiency [24]. Smaller, bio-inspired robots [1, 5, 6, 25] require significantly less optical power (100s of milliwatts), but only maintain flight for a few seconds.

Apart from aerial drones, optical power delivery has been explored for terrestrial drones which require considerably less power (10s of mWs) for locomotion [7, 26, 27]. Laser-based methods leverage high-power (10s of watts to multiple kilowatts) lasers [28–30] or resonant beams [31**?**] for power delivery and simultaneous communication [28, 30, 32–35].

Mobile Lasers and Tracking. Lasertag [9] leverages colocating tracking and positioning with laser steering. While there are benefits to solving depth ambiguity with colocation and a simpler mapping of pixel coordinates to steering angle, the main drawback is the loss of optical power with additional optical components such as a beamsplitter and fisheye lens. Furthermore, we hypothesize that higher-power infrared lasers could cause non-negligible damage to the event camera if colocated with a beamsplitter.

Event Cameras. Given its low latency, event cameras have been utilized heavily in drone-related research. Event-cameras have been placed on drones for high-speed obstacle avoidance [36, 37] and visual odometry [38, 39]. Other works have explored event cameras as detection mechanisms in remote stations such as with [40, 41] which all utilize the high-frequency characteristic of drone propellers to quickly detect drones within a scene.

Most relevantly, stationary event cameras have been used to track ground robots using frame-based tracking methods such as with Density-Based Spatial Clustering of Applications with Noise (DBSCAN) [42] and convolutional neural networks (CNN) [43]. Furthermore, real-time object tracking and actuation have been realized in systems such as a high-speed goalie system [44] where incoming balls were detected, tracked, and blocked using an event camera and servo motor system. The tracking involved a common method of event-based clustering called mean-shift clustering. Other methods of object tracking involve feature-based tracking such as with corners [38, 45] and with novel time-surface representations that efficiently capture both the events' spatial and temporal characteristics in a frame [36, 46]. While high-speed and real-time tracking is an ongoing research field, our preliminary system with ground robots does not require advances in this trajectory. The primary focus of this work is to optimize the existing methodologies which allows us to tackle the specific challenges associated with the high-resolution requirements of microrobot tracking without needing to reinvent the underlying algorithmic principles, which are already well-established and robust for broader applications. Hence, our tracking algorithm utilizes a modified version of the medoid-shift algorithm.

7 CONCLUSION

We demonstrated feasibility of laser-based wireless power transfer to a mobile target. The system utilized an event stream for tracking a mobile photovoltaic cell that can harvest power at high efficiency. We believe this work will lead to future explorations on making multi-robot systems more robust and potentially extending our work to aerial drones.

8 ACKNOWLEDGEMENTS

This work is supported in part by the National Science Foundation (DGE-2036197, CNS-1552924). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the funding agencies or others.

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