North Dakota Renewable Energy Council
Phase III Interim Report

Solar Soaring Power Manager

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Introduction

This document describes the accomplishments and current status of projects during phase III of the Solar Soaring Power Manager project. These activities took place at Packet Digital's facilities in Fargo, ND as well as at the Naval Research Lab (NRL) facilities. Progress has been made on all phase III deliverables and the project is on track as per the original proposal. A status update of each deliverable is listed below.

Objective:

This research and development project will create a solar soaring power management system for Unmanned Aircraft Systems (UAS) to initially double fly times and ultimately provide unlimited endurance powered by solar energy. This will be achieved by harnessing solar energy with high-efficiency, flexible photovoltaics and auto-soaring technology to enable the UAS to autonomously gain lift from rising hot air along with advanced power management algorithms. Packet Digital will create an advanced solar power management and distribution system (PMAD) combining flexible, high-efficiency power conversion circuitry to dramatically extend flight times in unmanned aircraft.

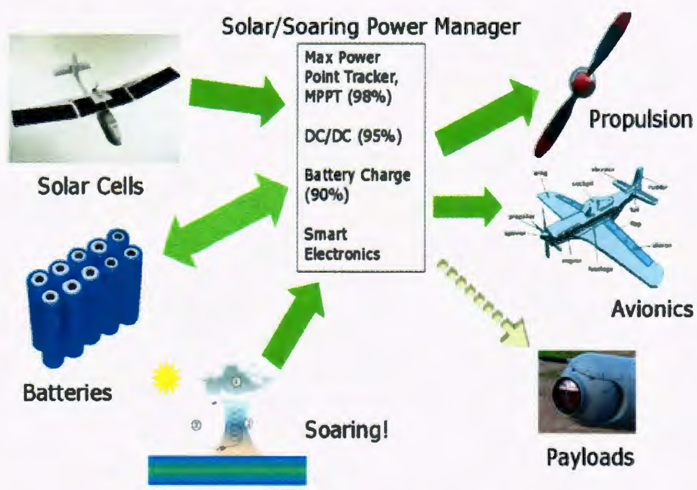

Figure 1: System Overview

This product will optimize the power conversion from the solar array to the batteries, from the batteries to the electronics, and from the batteries to the propulsion motor. The power conversion circuitry will provide state-of-the-art high efficiency power while the microprocessor will run advanced algorithms for maximum power point tracking and auto-soaring.

Schedule

This project is divided into three phases, of which phases I and II are of 9 month duration and phase III of 12 months. This interim report covers the progress made during months 1-3 of phase III.

Deliverables

Phase III Deliverables:

- Produce a solar cell covering the desired spectrum with 30-35% efficiency, with a target of 40%
- Perform multiple flight tests utilizing a solar enabled extended endurance UAS
- Achieve power management system with greater than 90% efficiency for typical loads, with a target of 95%, to extend battery life sufficiently to survive nighttime flight
- Innovate Maximum Power Point Tracker (MPPT) algorithm for extracting maximum charging capacity from the solar cells
- Develop a manufacturing plan for a commercial extended endurance solar UAS

Status Updates

Objective 1: Solar Cell Development

The NRL team continues solar cell development. The development of the 6 junction, III-V based solar cell is moving ahead. The initial 3 junction components are being produced and moving closer to the goal of 40% efficiency. At the same time, NRL is producing 3 junction, GaAs based solar cells and fashioning them into flexible solar arrays with nominal efficiency of ~27% when fully integrated. The individual solar cells produce between 30 and 33% efficiency. The arrays will be the first layer of the wing skin, and the work on the full wing build will start in December.

The NRL solar cell group is also developing extremely thin (on the order of 20 um) Si cells. With these paper-thin devices, the team will be able to produce solar arrays at 20% efficiency or higher that add essentially no additional weight to the aircraft. The commercial design for these cells is a flexible, robust, mono-crystalline, thin Si solar cell bonded to steel carrier that enables a lightweight, robust, glass-free module. These cells have demonstrated ~17% cell efficiency which is a world record for any silicon solar cell under 20 um thick (Fig 2). The goal is to archieve >23% efficiency with optimized materials and designs that are based on established volume production tools and processes.

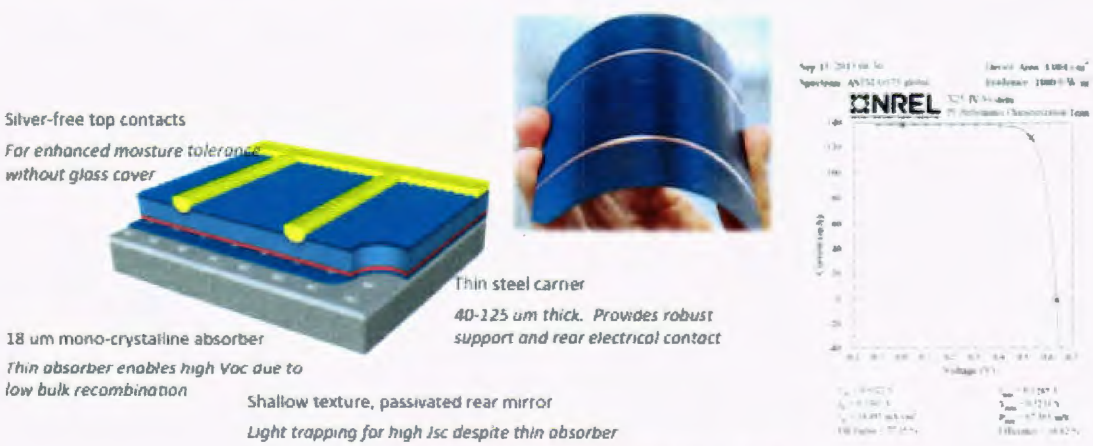

Figure 2: NRL Thin Solar Cells

Objective 2: Test Flights

During this reporting period, the NRL team focused mainly on the flight testing of the our solar extended endurance aircraft (Fig 3). The aircraft was fitted with solar cells. The cells were diced into thirds, and a total of 52 cells were incorporated into the UAS wings. The PV arrays were laminated and co-molded the wing and PV arrays. The power electronics system provided by Packet Digital consisting of the MPPT, PMAD, and smart battery were integrated into the aircraft. The takeoff mass was 6.8kg, of which 1.8kg was the battery.

Two test flights were performed. The first test flight was designed to provide initial flight data and uncover any integration issues. The flight time from takeoff to landing was a total of 81 minutes. The system consumed 119.2 Whr, at an average of 88.0 W. The solar array supplied 63.6 Whr of power and the battery supplied 55.9 Whr. The MPPT efficiency was 97.2%, and the battery state of charge (SOC) started at 99% and ended at 86%. The final results were that the array provided 53% of the energy while the battery provided 47% of the energy. It should be noted that only 3 of 4 sub-arrays were functional due to a manufacturing issue.

The measured output from the PMAD system is shown in Figure 4. The data shows how, after the initial take off, the system settles in for a relatively smooth flight where the system consistently provides steady 5 and 12 V power feeds to the UAS subsystems. The data displayed in Figure 5 shows the performance of the solar wings where the solar arrays tracked the solar insolation well and efficiency was measured around 20%.

The second test **flight featured the same aircraft but with all 4 solar sub-arrays functioning. The aircraft flew almost 11 hours, from sunrise to just before sunset,** with solar contributing more than 6 hours of the flight endurance -- a successful outing considering the highest insolation recorded that post-equinox day (October 14) was ~800W/m2, as compared to ~1100W/m2 that would occur in mid-June.

Figure 3: PV-SBXC aircraft with Si solar cells attached to the wings

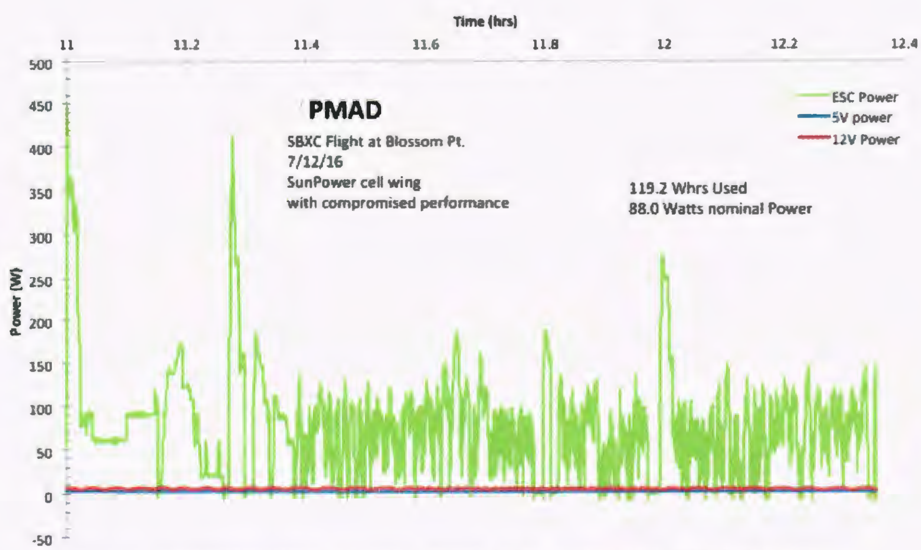

Figure 4: Measured output from the onboard PMAD system

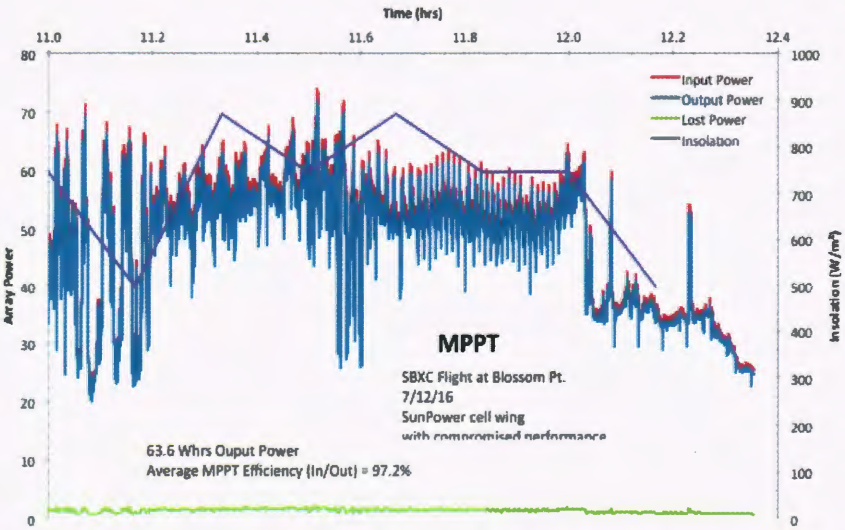

Figure 5: Measured data from the PV array on the wings during flight

Objective 3: Power Management Efficiency

An alternate version of the optimized electronic speed controller (ESC) was completed using a different microcontroller core and firmware from the previous version. The alternate microcontroller was chosen as it could support smaller current sense resistors and as a result higher motor current as the previous version could only support a maximum of 20A. Also, the alternate core supports the use of an over-modulation scheme which allows more thrust for high throttle ranges which was also a shortcoming of the previous controller.

The prototype of the alternate ESC is shown in the following figure. The board is 50mm x 32mm and weighs 44g. It supports up to a 6S configuration and will support up to 48A of motor current. Automated bench tests will be performed with the Neu 1110 motor and 13x11 graupner folding propeller to compare thrust efficiency against the data previously captured for the previous ESC design as well as the Castle Creations HV Edge Lite 40A controller.

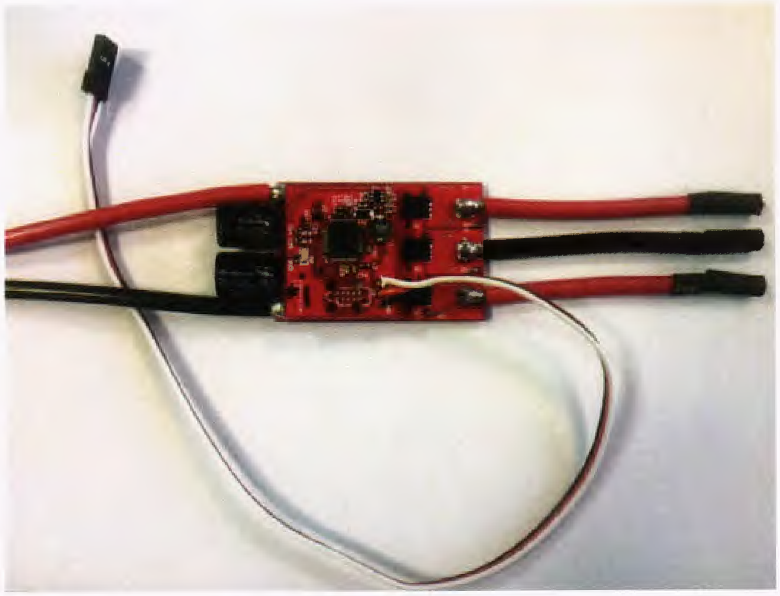

Figure 6: ESC Prototype

Objective 4: Maximum Power Point Tracker Update

During phase III, an MPPT test board was designed and fabricated in order to evaluate a new microcontroller as well as three different methods of measuring current. The board was assembled, tested, and compared against the existing MPPT developed in prior phases.

The purpose of the new microcontroller is to evaluate a potential upgrade to a more capable, higher performance, and lower cost microcontroller. Firmware was converted to the new microcontroller and equivalent functionality was obtained. Testing has shown that the new microcontroller is an adequate replacement and it will be used on all MPPTs going forward.

The three different current sense methods were evaluated to reduce cost and improve performance. Specialized current current sense transducers can be difficult to source, so finding an alternative with better availability is also a key objective. One architecture is based on resistive current sense, while the other two are based on hall effect sensing. Table 1 shows the results of the three options. While all the options performed well, option 1 has the lowest possible power consumption and also the lowest offset and error. This option also has the best availability. Based on this analysis, option one will be the new current sense circuit going forward.

	Pmin (mW)	Pmax (mW)	Iout Offset (mA)	Iout Expected Error (mA)
Option 1 (Resistive)	1.98	101.98	3.8	47.3
Option 2 (Hall #1)	39.6	99.6	56.7	88.8
Option 3 (Hall #2)	29.7	94.7	51.3	81.2

Table 1: MPPT Current Sense Comparison

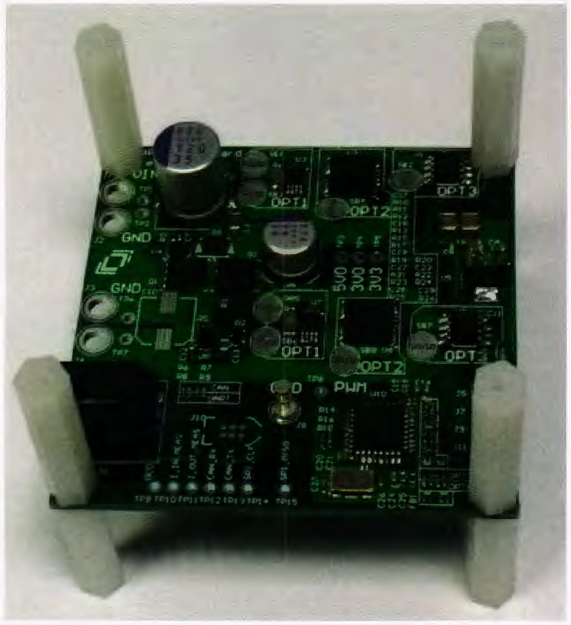

Figure 7: MPPT Test Board

Objective 5: Manufacturing Plan

Discussions have been held with Chiptronics LLC of Dunseith, ND regarding the assembling of the MPPT and PMAD PCBs. Chiptronics is capable of performing the assembly work and pricing discussions have been initiated.

Work has also been initiated with c2renew, Inc of Fargo, ND on the assembly of the solar wings. Molds for the wings have been designed and are currently being manufactured. Flex circuits have been delivered and the solar cell lamination process is being defined and tested on samples.

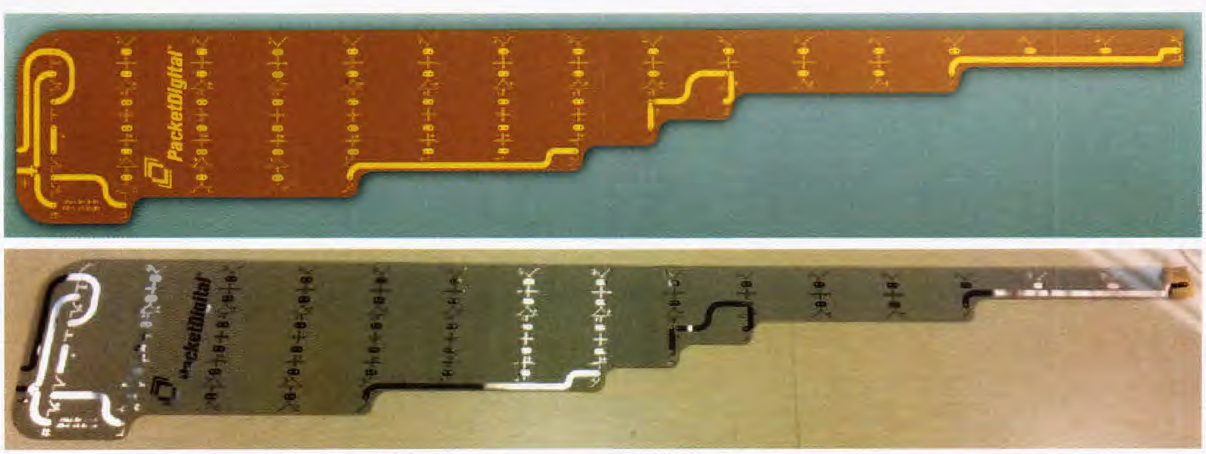

Figure 8: Flex Circuit CAD Drawing (above) and Prototype (below).

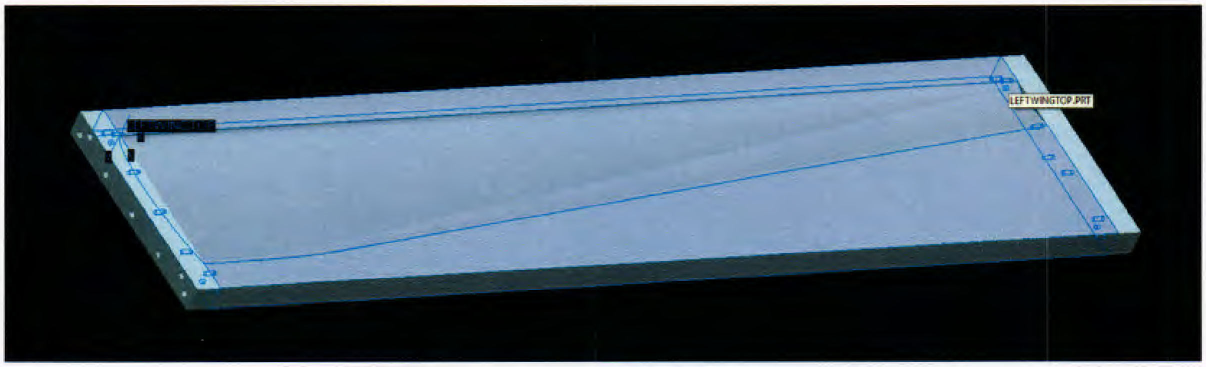

Figure 9: Mold CAD Drawing

Figure 10: Wing Mock-up With Solar Cells

Other activities:

Packet Digital met with representatives from the Grand Sky UAS Business and Aviation Park to discuss the details of conducting a test flight in North Dakota. Flying at Grand Sky could potentially allow flights above 400' as limited by the FAA Part 107 rules.

Budget

Total project cost for phase III is expected to be $1,000,000, of which $375,000 is provided by NDIC, and $625,000 is provided by the Naval Research Lab as matching funds. Table 2 lists the budget estimate for Phase III and Table 3 lists the budget status as of November 30, 2016.

Project Associated Expense	NDIC's Share	Naval Research Lab Share	Total
Total Personnel Costs	$265,000	$505,000	$770,000
Software Costs/Materials	$110,000	$120,000	$230,000
Total	$375,000	$625,000	$1,000,000

Table 2: Phase III Budget Estimate

Project Associated Expense	NDIC's Share	Naval Research Lab Share	Total
Total Personnel Costs	$124,893		$124,893
Software Costs/Materials	$59,774		$59,774
Total	$184,667	$300,000	$484,667

Table 3: Interim Budget Status as of November 30, 2016

Summary

Phase III Deliverables:

- Solar cell development
    - NRL has continues to make progress on the multijunction cells, both type III-IV and GaAs cells.
    - Work has also been done on producing lightweight, robust, glass-free modules that can be integrated into the UAS with almost no increase to the system weight.
- Test flights
    - Initial solar test flights with the NRL at Aberdeen Proving Grounds were successful at proving the validity of the Packet Digital power system as well as the solar powered system. The flight was scheduled from sunup to sundown. The extended endurance aircraft flew the scheduled nearly 11 hours and landed with a charge on the battery.
- Power Management System
    - An updated and improved ESC has been designed and is demonstrating good functionality. Additional testing is ongoing.
- Maximum Power Point Tracker

  - An MPPT board with various design options was designed and characterized. This has provided data to optimize the MPPT in terms of size, weight, cost, and performance.
  - A new MPPT based on the best options from the test MPPT is currently being designed.

- Manufacturing Plan
  - Working with Chiptronics, LLC regarding the assembly of the power electronics
  - Custom solar wing mold design is complete and queued for fabrication through c2renew, Inc.
  - Solar cell lamination process is also being refined.

Significant progress has been made in phase III of this project and Packet Digital is on track to have a complete the objectives as per the original project timeline. NRL is also on track in terms of the solar cell development.