North Dakota Renewable Energy Council
Final Report

Solar Soaring Power Manager

Phase I

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Introduction

This document describes the accomplishments and current status of projects during Phase I 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 I 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 provide on the order of 16 hours of flight endurance, depending on solar input, 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 and advanced power management algorithms.

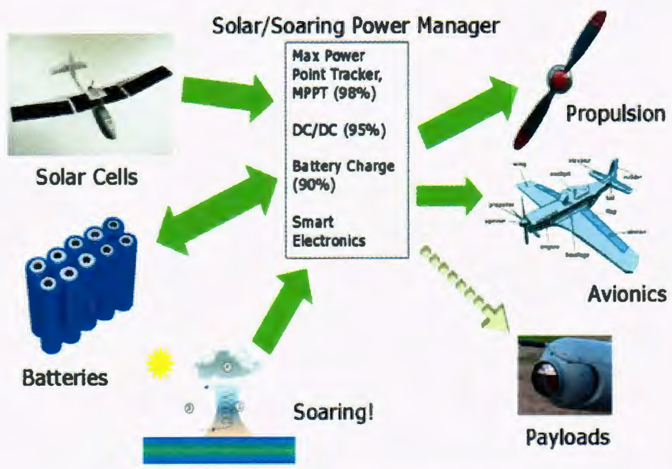

Figure 1: System Overview

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 6 months. This final report covers the progress made through Phase I of the project.

Deliverables

Phase I deliverables:

- Produce a solar cell covering the desired spectrum with 30-35% efficiency, with a target of 40%
- Develop an algorithm for achieving Maximum Power Point Tracking (MPPT) for the prototype solar cell
- Create a prototype power management solution with greater than 90% efficiency, with a target of 95%
- Define the architecture for the power electronics solution to be implemented in custom silicon
- Develop improved soaring algorithms based on the mathematical model for thermal updrafts
- Test all prototyped solutions integrated in a lab environment

Phase I Deliverable Results

Solar cells:

At the end of Phase I, individual solar cells with an efficiency of 37.8% were obtained. NRL has identified straightforward solar cell design improvements, which are expected to increase efficiency near 40%. In addition to increasing efficiency, NRL has initiated manufacturing of flexible solar arrays suitable for UAV wing mounting at several manufacturing partners. These include 22% Si and 27% GaAs solar arrays. Figure 2 shows the cell layout of GaAs solar cells on the SBXC inner wing section. Fully assembled wings are expected September 1.

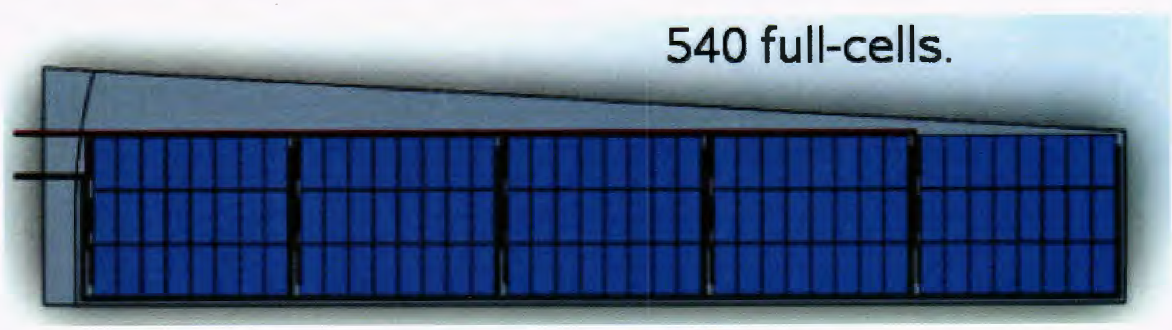

Figure 2: Inner Section of SBXC Wing with Solar Cells

To achieve higher efficiencies, NRL is developing stacked multi-junction (MJ) solar cells. This technology takes advantage of transfer printing, which is a technique enabling direct integration of dissimilar materials into a single device. With the range of materials provided by the transfer printing technique, NRL has created solar cell designs capable of achieving greater than 40% conversion efficiency. NRL has established a contract with a third party that has commercialized the transfer printing technique for solar cell applications. NRL will provide solar cell materials to the third party who will fabricate them into stacked MJ devices. It is expected that these devices will be available to enable higher-efficiency panels for the second phase of the solar UAS project.

Maximum Power Point Tracker:

The design and fabrication of a UAV-specific maximum power point tracker (MPPT) converter was completed in Phase I. The SS-MPPT01 has rapid convergence in order to maintain maximum power extraction from the solar cells during flight maneuvers. A perturb and observe algorithm with adaptive step size has been implemented in hardware. The adaptive step size allows quick convergence while maintaining stability. Figure 3 shows the final hardware device. Table 1 show the device specifications.

Figure 3: SS-MPPT01 Device

Nominal Output Configuration	6s Lithium Ion
Converter Architecture	Boost
Input Voltage Range	14 to Vout (UVLO at 14V nominal, adjustable with resistors)
Output Voltage Range	Vin to 25.2V (OV trip at 27V)
Absolute Max Voltage	35V (input and output)
Maximum Current	10A (input and output)
Over-temperature Threshold	60C with 5C Hysteresis
Switching Frequency	250 kHz
MPPT Update Frequency	1024 Hz
Dimensions	2.5" (2.72" including J1 header) x 2.25" x 0.73" (L x W x Thickness) 63.5 (69.1 including J1 header) x 57.2 x 18.5 mm
Mounting holes	0.25" (6.3 mm) from board edges at corners
Weight	1.6 oz (45 g)

Table 1: SS-MPPT01 Specifications

The typical power conversion efficiency is shown in Figure 4 below.

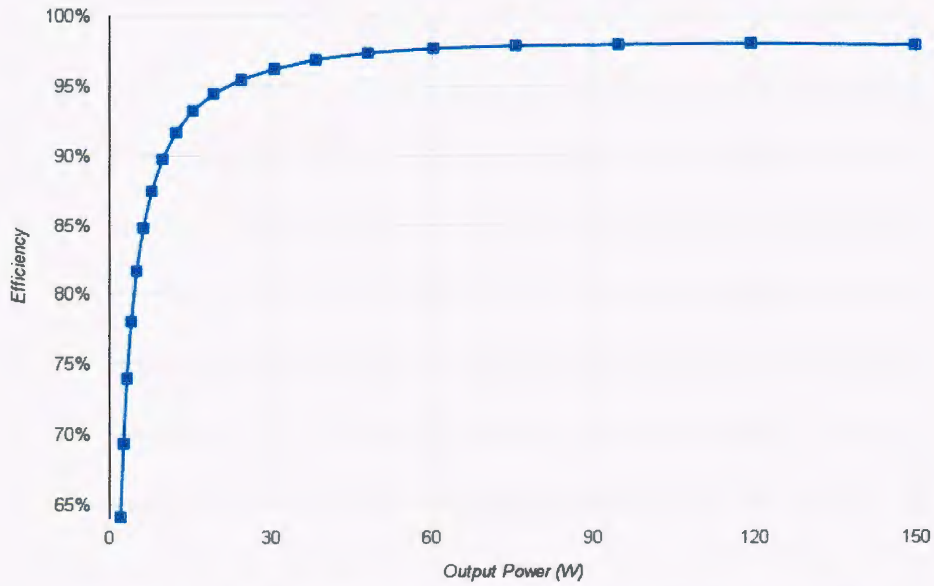

Figure 4: SS-MPPT01 Typical Efficiency vs. Output Power

Power Management and Distribution System

The SS-PMAD01 implements a power management and distribution (PMAD) system for use in unmanned aircraft. It provides 5V and 12V power for flight electronics and payloads and serves as a power and communications hub for batteries and photovoltaic (PV) power sources. Telemetry data from the batteries and PV sources is passed along with additional measurements from the PMAD and is available on a serial port for downlink. The SS-PMAD01 is shown in Figure 5. Specifications are listed in Table 2.

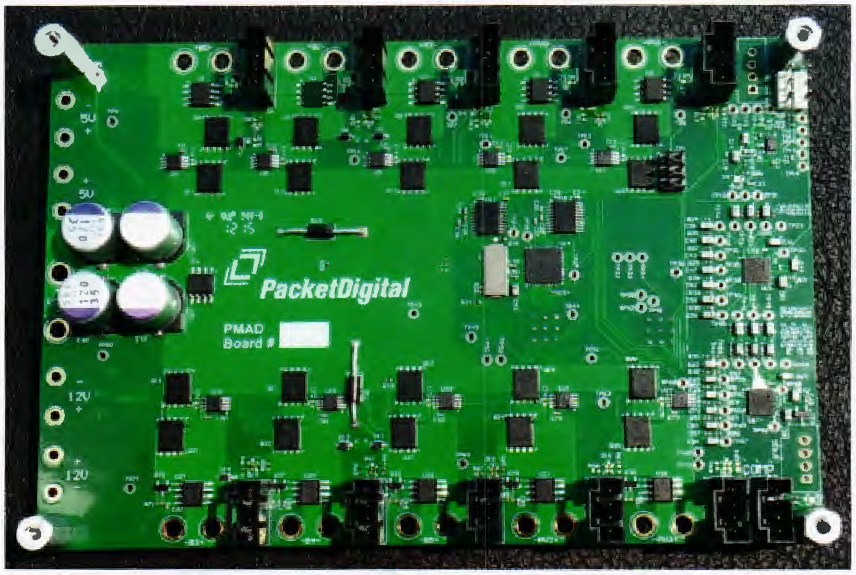

Figure 5: Power Management and Distribution PCB

MPPT and Battery Voltage	15-28V
Battery Current	30A Discharge, 20A Charge (per battery)
MPPT Current	10A (per MPPT)
ESC Current	30A
5V Current	8A
12V Current	4A
Dimensions	6.000 x 4.000 x 0.765 in (L x W x H) 152.4 x 101.6 x 19.4 mm
Mounting Holes	0.150 in (3.8mm) from edges at each corner
Weight	3.45 oz (98 g)

Table 2: SS-PMAD01 Specifications

Performance testing has shown that the PMAD achieves 95.6% efficiency on the 5V supply and 97.2% efficiency on the 12V supply. Full efficiency curves covering the entire load current range are shown in Figures 6 and 7.

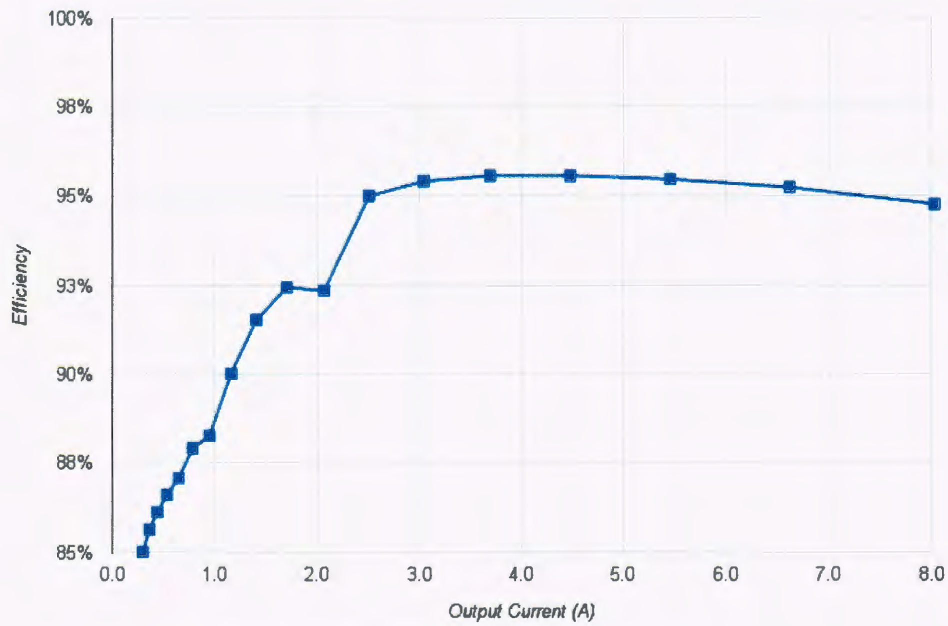

Figure 6: PMAD 5V Efficiency vs. Load

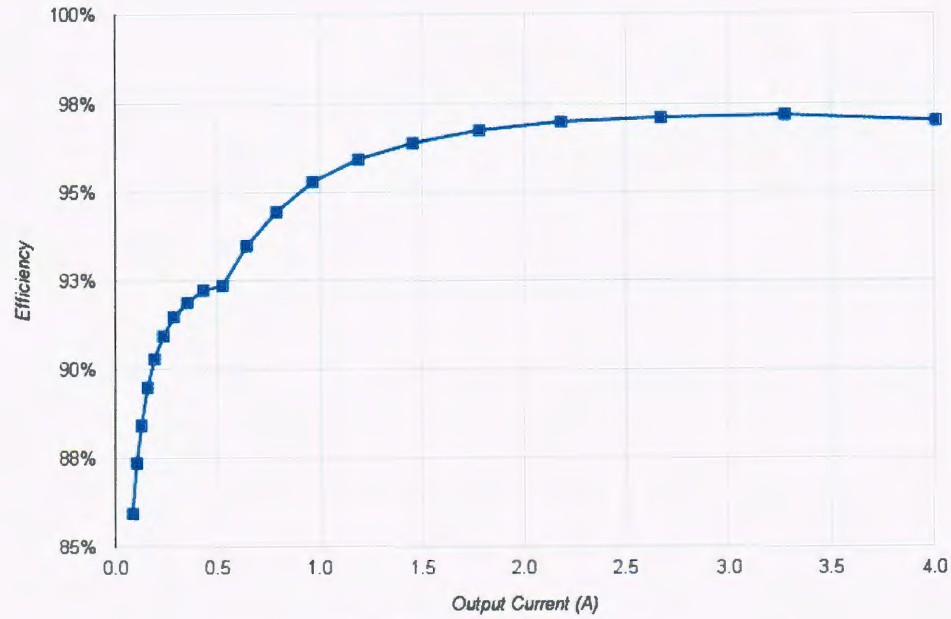

Figure 7: PMAD 12V Efficiency vs. Load

Custom Silicon Power Management Integrated Circuit

The high level architectural details of the PMIC is confidential and included in the appendix.

Smart Battery

The SS-SB01 UAS smart battery features integrated charging, balancing, over-voltage protection, over-current protection, temperature monitoring, and fuel gauge monitoring. Voltage, current, state of charge, remaining capacity, and other battery health information is transmitted periodically to the PMAD. Two units have been built and gone through several charge-discharge cycles. Figure 8 shows the battery configuration. Figure 9 shows the final unit. The SS-SB01 is wrapped in foam for protection during UAV landings.

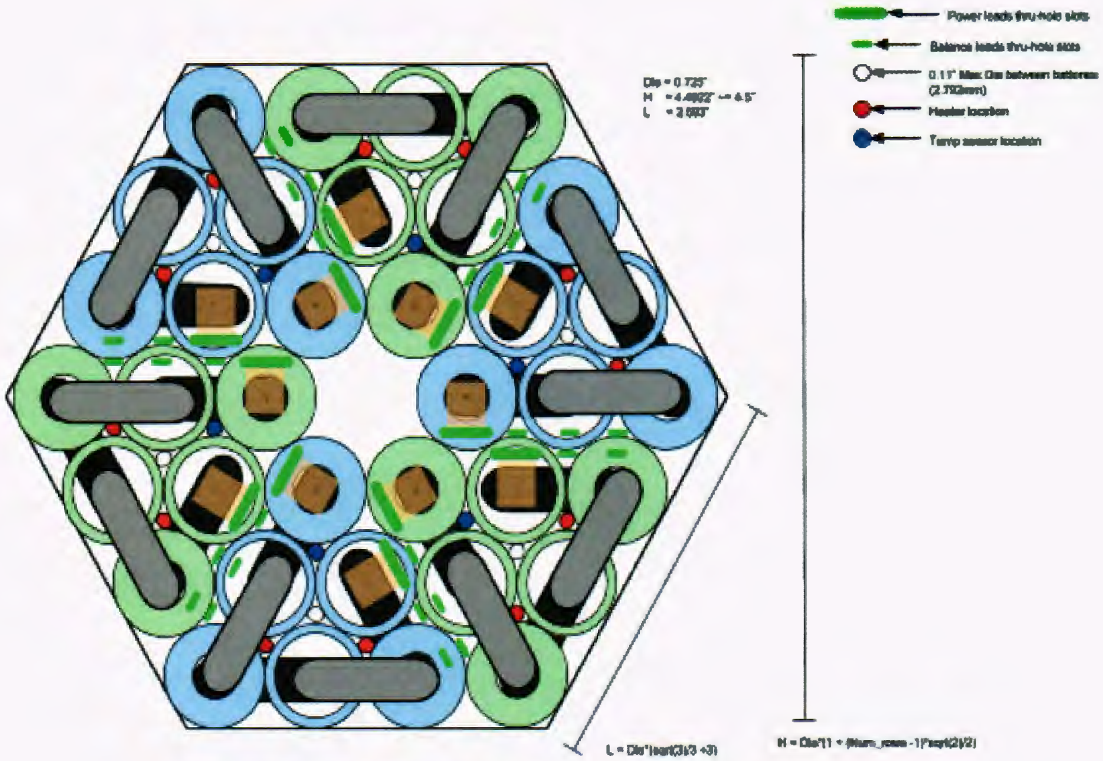

Figure 8: SS-SB01 Smart Battery Physical Configuration

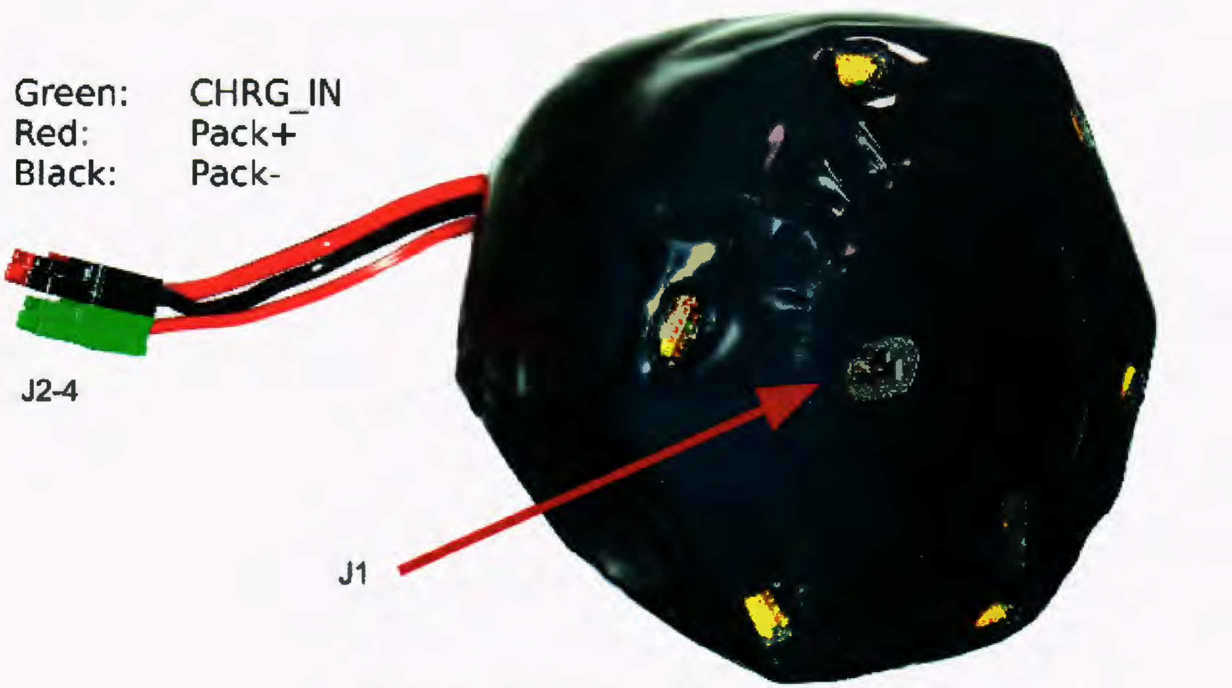

Figure 9: SS-SB01 Smart Battery

Cell count/config	36 cells in 6S6P configuration
Voltage	21.6V(nominal), 25.2V(max)
Current	9.75A (max charge), 39.0A (max discharge)
Balancing Current	19.5mA
Capacity	18720 mAh (nominal)
Weight	4.20 lb, 1.91 kg
Dimensions	5.45 x 5.20 x 4.00 in (WxLxH) 138 x 132 x 102 mm
Wall supply	150W 28V DC 5.36A
Temperature range	0 to 45C (charge), -20 to 60C (discharge), -20 to 50C (storage)

Table 3: SS-SB01 Specifications

Soaring Algorithms

The NRL soaring algorithm math has been transcribed from the original Matlab source code into an NRL Report that documents the raw mathematics, state machines, and logic flow. Necessary inputs to the soaring algorithms are the sink polar (power-required curve) of the aircraft and the propulsion system coefficient of thrust vs. advance ratio mapping. The power-required curve was measured during the December flight test and post-processed to produce the sink polar. This curve also provides input to the power budgeting analysis. The propulsion system has been duplicated in a fixed stand mount that bolts to the NRL low-speed wind tunnel balance and is undergoing final preparations for the wind tunnel testing process.

Packet Digital is in the process of developing a real-time embedded flight computer that will run the soaring algorithms. This work will continue in Phase II, including test flights.

Ground Testing

Lab testing of the MPPT, PMAD, and smart battery has been successfully conducted. The MPPT was powered by a solar array simulator. The load was the UAS motor, which was tested up to 580W. Status of the system was monitored during operation and behavior was as expected.

Power Budget Analysis

NRL built a power budget model of the developmental system to estimate the endurance using photovoltaics (solar arrays) alone. This model includes measured aerodynamic performance from the NRL flight tests, measured battery performance, estimated photovoltaic (PV) array performance with specified array geometry, and no soaring power input. The environmental model is based on National Renewable Energy Laboratory (NREL) measurements at various locations around the U.S., averaged over each month, and therefore includes incidence angle effects, haze, clouds, and other sources of variability. Using this model, the prototype aircraft is assumed to be launched at 4 hours before sunrise. It then flies throughout the daylight hours and recharges the battery to a degree variable with the latitude, and then flies into the night approximately 3 hours before the battery is exhausted. Figure 10 shows the preliminary power budget model results for Fargo, ND in September.

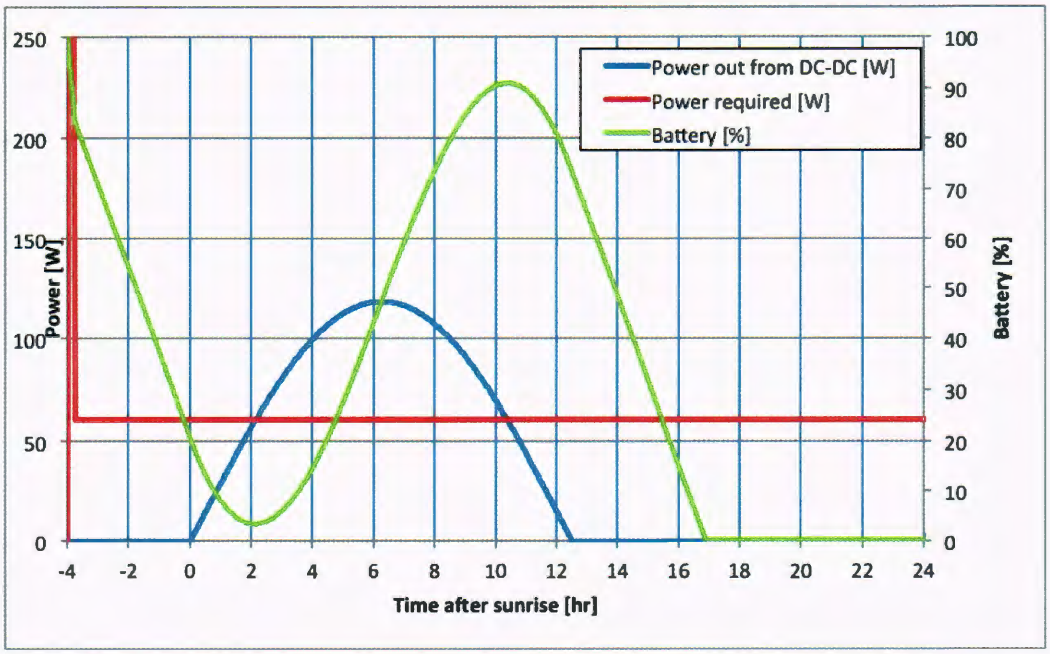

Figure 10: Prototype aircraft power budget estimate for Fargo, ND in September

Caution should still be taken using the endurance value from this preliminary model. As more component efficiencies are measured, the fidelity of the model will improve. Inaccuracies in the propulsion system model, in particular, are extremely sensitive and result in large swings of the estimated total endurance.

Prototype Flight Testing

NRL conducted three flight tests with the prototype SBXC aircraft for a total of six flights. Figure 11 shows the aircraft on takeoff and landing. Note that the two center wing panels will be replaced with the solar photovoltaic wings, once available.

Figure 11: Prototype SBXC hand-launched takeoff (left) and belly-landing (right).

Three flights on July 31st served as an aircraft checkout and pilot refresher day. This familiarized the flight crew with the flight characteristics of the SBXC.

Two flights on November 19th tested a significant rebuild of the internal system configuration of the SBXC, after removing previous autonomous soaring hardware (RxMux safety switch, Skymelody variometer, JR RC system, old propulsion system, excess wire weight) and replacing with all new hardware (Piccolo SL, new wiring, new propulsion system). Two different propellers were flown to confirm the climbout performance under manual control.

One flight on December 15th tested a new 6s6p battery built from 18650 cells in the smart-battery configuration, but without the smart-battery circuitry. The primary purpose of the flight was to measure the in-flight power required curve using a custom power logger. Speeds from 20 to 30kts were measured in 1kt increments and from 30 to 45kts measured in 5kt increments to determine the minimum-power-required speed of 25kts and 65W for a flight weight of 6.56kg.

Also on the December 15th flight was an onboard solar irradiance measurement system, with sensors on the leading and trailing edges of both left and right wings, and one on the fuselage. The aircraft was flown in both wings-level rectangular box patterns and in concentric orbits at decreasing radii to simulate autonomous soaring maneuvers. This data is valuable for the design of the MPPT algorithm and electronics as it gives the team real-world flight irradiance dynamics. This data was utilized in the MPPT simulations to verify the algorithm's ability to meet the needs of the expected UAS flight maneuvers.

Other Activities:

Packet Digital recently announced the formation of Botlink, a joint venture between Packet Digital and Aerobotic Innovations. Botlink will produce a software platform solution to safely and securely control UAS.

Packet Digital met with representatives from the Northern Plains Unmanned Systems Test Site to discuss the details of conducting a test flight in North Dakota. Significant progress was made and discussions will continue as the UAS nears flight-readiness.

Budget

Total project cost for Phase I was expected to be $1,010,000, of which $500,000 is provided by NDIC, and $510,000 is provided by matching funds. Of the matching funds, $260,000 is provided by the Naval Research Lab and $250,000 is from Packet Digital. Table 4 lists the budget estimate for Phase I and Table 5 lists the budget status at the completion of Phase I (July 2015).

Project Associated Expense	NDIC's Share	Private Sponsor Share	Naval Research Lab Share	Total
Direct Personnel Costs	$215,000	$122,000		

Indirect OH and G&A (65%)	$139,500	$79,000		
Total Personnel Costs	$354,500	$201,000	$222,000	$777,500
Software Costs	$86,000	$49,000		$135,000
Materials	$59,500		$38,000	$97,500
Total	$500,000	$250,000	$260,000	$1,010,000

Table 4: Initial Phase I Budget Estimate

Project Associated Expense	NDIC's Share	Private Sponsor Share	Naval Research Lab Share	Total
Direct Personnel Costs	$184,587	$103,831	-	-
Indirect OH and G&A (65%)	$119,680	$67,320	-	-
Total Personnel Costs	$304,267	$171,151	$222,000	$697,418
Software Costs	$136,233	$68,689	-	$204,922
Materials	$59,500	$54,663	$38,000	$152,163
Total	$500,00	$294,503	$260,000	$1,054,503

Table 5: Final Phase I Budget Status

Summary

Phase I Deliverables:

Target: Produce a solar cell covering the desired spectrum with 30-35% efficiency, with a target of 40%

Result: 37% efficiency has been achieved in the lab, a path to 40% identified, and manufacturing of 27% efficiency cells has begun.

Target: Develop an algorithm for achieving Maximum Power Point Tracking (MPPT) for the prototype solar cell

Result: MPPT hardware is complete in a small package (45g) with rapid convergence (1kHz update frequency).

Target: Create a prototype power management solution with greater than 90% efficiency, with a target of 95%

Result: PMAD achieves 97.2% (12V) and 95.6% (5V) efficiency.

Target: Define the architecture for the power electronics solution to be implemented in custom silicon

Result: Architecture has been defined.

Target: Develop improved soaring algorithms based on the mathematical model for thermal updrafts

Result: Hardware prototype for onboard algorithm execution is complete.

Target: Test all prototyped solutions integrated in a lab environment

Result: Entire system functions together in a mock-UAS setup.

During Phase I, NRL made significant progress increasing the efficiency of solar cells, including flexible cells required for mounting on a UAS. Packet Digital successfully completed the design of the solar soaring UAS power delivery system. The MPPT, PMAD, and smart battery are working together as per requirements. A custom UAS integrated circuit architecture has been defined, and a full system test flight is scheduled for September.