North Dakota Renewable Energy Council
Interim Report

# Solar Soaring Power Manager


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## Introduction

This document describes the accomplishments and current status of projects during phase II 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 II 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.

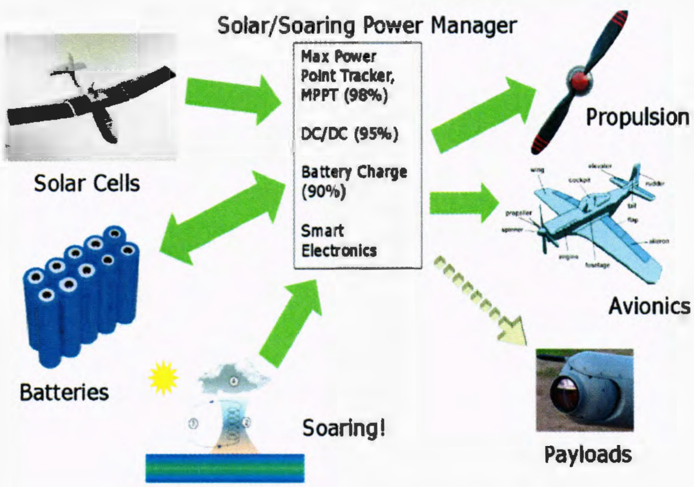


**Figure 1: System Overview**

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 6 months. This interim report covers the progress made during the first 3 months of phase II.

## Deliverables

Phase II Deliverables:

- Produce a solar cell covering the desired spectrum with 30-35% efficiency, with a target of 40%
- Implement solar soaring algorithms into a prototype of a commercially feasible product
- Design a Maximum Power Point Tracker (MPPT) and Power Management and Distribution (PMaD) system that is compatible to the commercial industry standards for unmanned aircraft that improves the performance of Unmanned Aircraft Systems (UASs) similar to the Altavian UAS manufactured by ComDel. The industry compatible system will be integrated into a solar unmanned aircraft and tested at the Northern Plains Test Site.
- Develop a hybrid smart battery combining multiple storage technologies to be charged by solar in flight
- Produce an optimized torque motor control prototype, with a target of improving propulsion system efficiency 5% and reducing airframe vibration
- Test all prototyped solutions integrated in a lab environment

## Status Updates

### Objective 1: Solar Cell Development

To achieve eternal endurance UASs, the US Naval Research Laboratory (NRL), in partnership with Packet Digital, has been developing high efficiency solar cells in a flexible format that can directly integrated to the wings of an airplane. In Phase 1 of this project, NRL demonstrated individual solar cells with an efficiency of 37.8%. NRL also initiated efforts to develop a methodology for manufacturing of flexible solar arrays suitable for UAS wing mounting at several manufacturing partners.

In Phase II of this effort, NRL continued development of the high efficiency, stacked multi-junction solar cells. This effort focused primarily on optimizing the multi-junction solar cell stack to achieve the highest efficiency possible utilizing the NRL Multibands software that allows the modeling and simulation of multijunction solar cells of various configurations. The modeling efforts resulted in two promising designs, one using an InP based bottom cell and the other using a GaSb based bottom cell. Both designs utilize a GaAs based top cell. NRL performed a series of epitaxial growths to produce the semiconductor materials needed to fabricate these cells. These cells are currently in the fabrication laboratory at NRL and measured results are expected in early January 2015.

Also in Phase II, Packet Digital and NRL explored other options to obtain solar cells that are suitable for integration onto the UAS wings. In this effort, various solar cell technologies were considered where solar cell performance was balanced against cost and availability. Two solar cell technologies were identified as viable candidates for this effort. One technology is the inverted metamorphic (IMM) solar cell being developed by several laboratories in the US and abroad. NRL has been working for several years on advanced IMM cells and has already demonstrated backpack mounted solar blankets for USMC applications, and as part of the ND-REC effort, this design was modified to allow the IMM array to fit onto the UAS wing. These arrays have been produced with an efficiency of ~27% and an output of 127W under standard illumination conditions. NRL is currently building up the wings using the solar arrays as the outermost layer of the wind skin. The wings are expected to be completed by the end of the calendar year in time for flight-testing in early 2016.

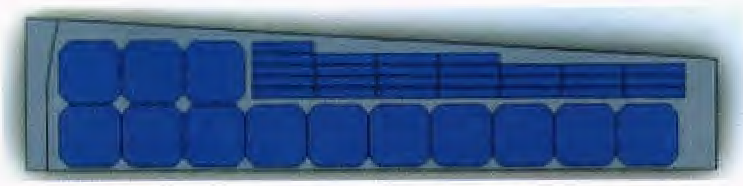

**Figure 2: 34.7 full-cell equivalent solar wing layout (right wing half)**

**Figure 3: Prototype cell layout (left wing half)**

## Objective 2: Update Power System to Support Commercial UAS

In phase II, the power electronics for the phase I fixed wing UAS were optimized for use in other airframes. The primary means of optimization was using a smaller form factor and adding the CAN communication scheme.

The maximum power point tracker (MPPT) from phase I has been optimized for size and efficiency. The enabling technology for the optimization is the use of Gallium Nitride (GaN) transistors. GaN transistors feature lower $R_{DS,on}$ and less capacitance in a smaller package than silicon transistors. The lower capacitance allows for faster regulator switching frequencies, which also enables the use of a smaller inductor, which is the physically largest component on the MPPT board. The initial version of the GaN MPPT board has been manufactured and is currently being tested.

**Figure 4: GaN MPPT**

A smaller form factor power management and distribution (PMAD) board was also developed (PMAD Lite). The original PMAD supported up to six batteries and four MPPTs. The PMAD Lite supports one battery and one MPPT, which is sufficient for many applications.


**Figure 5: PMAD Lite**

The PMAD Lite is now installed in the Naval Research Lab's airframe and has passed the first full functional test, and will undergo more strenuous bench testing. The first test flight with the PMAD Lite will be in January, weather permitting, at the Aberdeen proving ground in Maryland.

## Objective 3: Hybrid Smart Battery

Initial work during phase II on the hybrid smart battery has focused on hydrogen fuel cell technology. Hydrogen fuel cells have a very high energy density, but also environmentally friendly as their byproduct are only electricity, heat and water vapor. As an added benefit, the thermal energy generated by the fuel cell during the reaction can be harvested to generate electricity for further fuel efficiency improvement. This can be done for example by using thermoelectric generator (TEG) module. While not rechargeable in flight, fuel cells are attractive as they would provide power to the UAS during periods when solar power is not available.

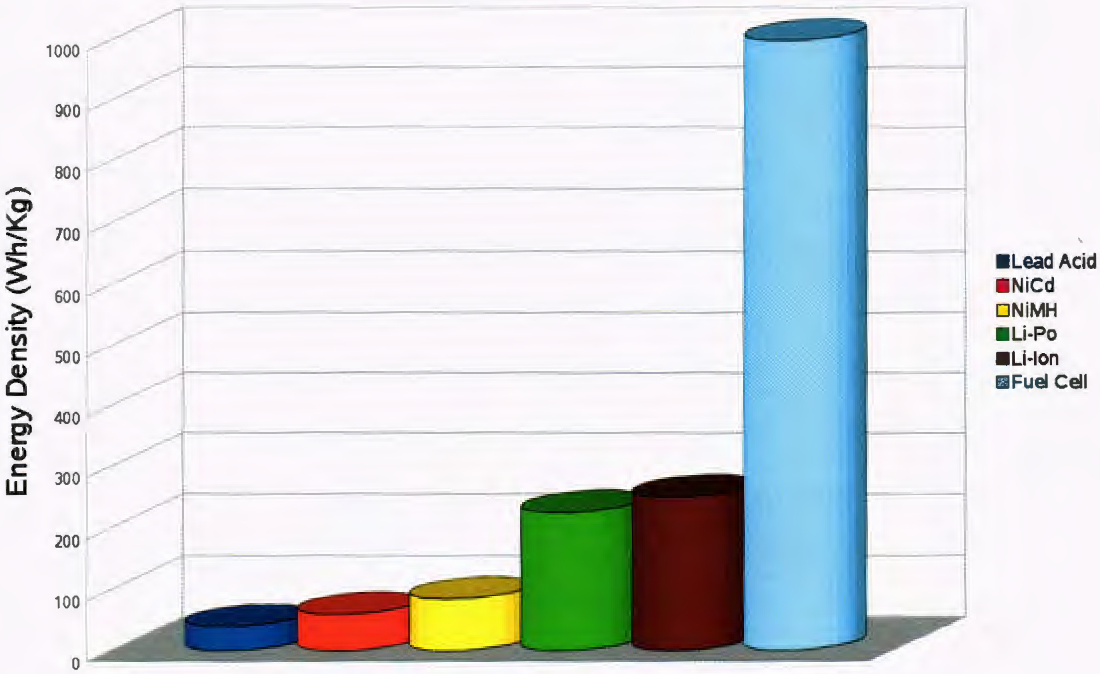


**Figure 6: Fuel cell energy density comparison**

Discussions have been initiated with several leading UAS fuel cell providers. Fuel cells are available in the 200W-1000W power levels with gas, liquid, and solid fuel technologies. Technical details are being gathered in order to do an in-depth comparison. However considering the size and weight of the fuel cell system, power level between 200W to 500W will likely be the initial choice for this phase II.

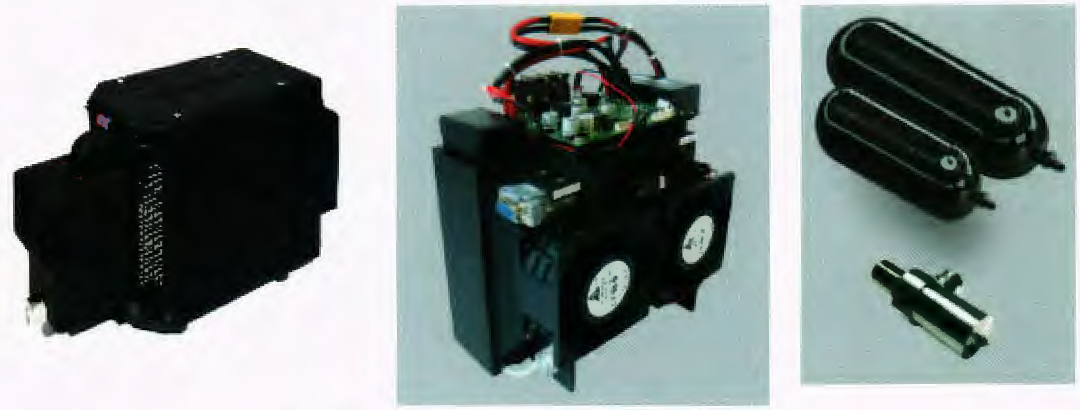

**Figure 7: UAS Compatible Fuel Cells**

### Objective 4: Optimized Torque Motor Control

The vast majority of electronic speed controllers (ESC) for UAS motors utilize a common control method which applies battery voltage and therefore current, which is proportional to torque, to the drive the motor in order to control the speed of the motor. This control method is simple and very economical to implement and supports a wide range of motors without knowing their specifications. Other forms of motor control exist that are application specific and computationally intensive, and until recently were considered too uneconomical for motors used in UAS applications. These control methods calculate the minimal amount of current (torque) required to achieve the desired speed efficiently and apply the current in a way that reduces vibration. These torque control methods have been strictly applied to industrial sized motor applications and were not considered to have benefits for small UAS motors. Advances in semiconductor technology and increased desire for higher efficiency of UAS applications has the potential for improved torque control for UAS motors resulting in smoother operation and gains in efficiency. A prototype design is underway and is currently being tested with the airframe motor. Performance measurements are in progress utilizing prototype hardware.

### Objective 5: Implement Solar Soaring Algorithms

An embedded flight computer has been developed for running the solar soaring algorithms. This flight computer consists of a Intel Edison board which serves as a processing platform to run the soaring algorithms and a cellular modem for communication. The platform hardware has been tested in flight and software development is in progress. Conversion of the Matlab source code is the next step in the implementation process.

### Other activities:

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 II was expected to be $1,000,000, of which $350,000 is provided by NDIC, and $650,000 is provided by matching funds. Of the matching funds, $600,000 is provided by the Naval Research Lab and $50,000 is from a private investor. Table 1 lists the budget estimate for Phase II and Table 2 lists the budget status as of December 31, 2015.

**Table 1: Phase II budget estimate**

| Project Associated Expense | NDIC's Share | Private Sponsor Share | Naval Research Lab Share | Total |
|---|---|---|---|---|
| Direct Personnel Costs | $181,200 | $ | | |
| Indirect OH and G&A (65%) | $117,800 | $ | | |
| Total Personnel Costs | $299,000 | $ | $486,000 | $785,000 |
| Software Costs/Materials | $51,000 | $50,000 | $114,000 | $215,000 |
| Total | $350,000 | $50,000 | $600,000 | $1,000,000 |

**Table 2: December interim budget status**

| Project Associated Expense | NDIC's Share | Private Sponsor Share | Naval Research Lab Share | Total |
|---|---|---|---|---|
| Direct Personnel Costs | $64,001 | $0 | - | - |
| Indirect OH and G&A (65%) | $41,496 | $0 | - | - |
| Total Personnel Costs | $105,497 | $0 | $112,786 | $218,283 |
| Software Costs/Materials | $15,019 | $14,430 | $37,595 | $67,044 |
| Total | $120,516 | $14,430 | $150,381 | $285,327 |

## Summary

Phase II Deliverables:

- Solar cell development
    - NRL is currently developing inverted metamorphic solar cells with a third party with the potential to achieve between 30 and 33% efficiency. During this phase I these solar cells will be integrated into the UAS wings and included in the initial solar UAS flight testing.
- Update power system to support commercial UAS
    - Initial prototypes of the smaller, more flexible MPPT and PMAD have been received and are undergoing testing.
- Hybrid smart battery
    - Initial hybrid smart battery design is underway. Discussions have been initiated with commercial UAS fuel cell vendors. Feature and cost comparisons are in progress.
- Optimized torque motor control
    - A prototype design is underway and is currently being tested with the airframe motor. Performance measurements are in progress utilizing prototype hardware.
- Implement solar soaring algorithms
    - The platform hardware has been tested in flight and software development is in progress. NRL has performed flight tests in early November at Aberdeen Proving Grounds and logged more than 12 hours of flight time, including more than two hours of latched thermal soaring. Conversion of the MATLAB source code is the next step in the implementation process.

Significant progress has been made in phase II 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.