North Dakota Renewable Energy Council
Final Report

Solar Soaring Power Manager

Phase II

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Introduction

This document describes the accomplishments 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 U.S. Naval Research Laboratory (NRL) facilities. Significant progress has been made on all phase II deliverables and the project is on track as per the original proposal. The final result 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.

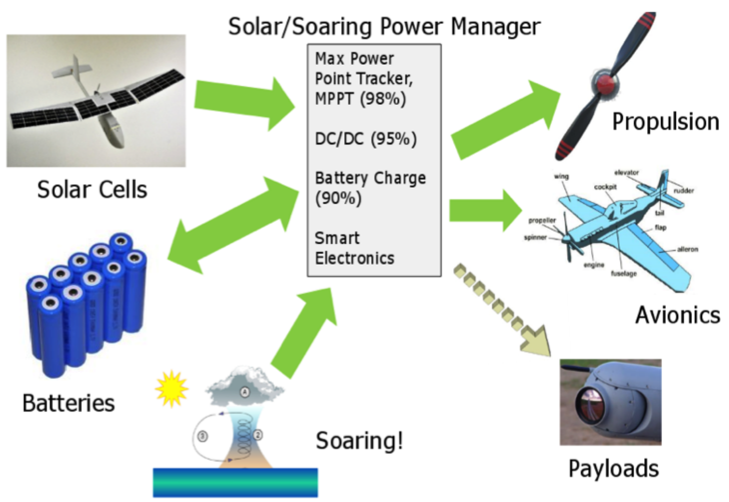

Figure 1: System Overview

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 final report covers the progress made during 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

Phase II Deliverable Results

Objective 1: Solar Cell Development

During phase II, NRL continued development of the high-efficiency solar cells and the integration of the solar arrays on to the wings of the UAS.

The highest performing solar cells are based on multijunction (MJ) technology in which various semiconductor materials are combined to achieve maximum solar absorption and, most importantly, highest solar-to-electric energy conversion. The NRL Multibands software was used to model and simulate the multijunction solar cells for use on the UAS wings. The results of the modeling established a six-junction solar cell design capable of achieving 40% efficiency.

Based on the software model and simulation, several material growth runs were completed. These were initial material growth runs consisting of 3-junction cells based on Gallium Arsenide (GaAs) stacked upon 2 junction cells based on Indium Phosphide (InP). Figure 2 below shows the full, 5-junction device, where a visible image shows the top, GaAs, 3-junction cell and a IR image shows the bottom, InP, 2-junction cell. These cells demonstrated efficiencies of nearly 37%. The next stage is to establish the full 6-junction cell using Gallium Antimonide (GaSb) bottom cells where efficiency of ~40% is expected.

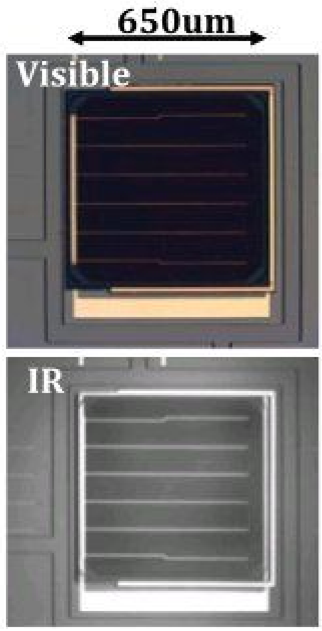

Figure 2: Photograph of a stacked cell. Top picture (visible) shows the GaAs-based cells, the bottom figure (IR) shows the bottom, InP cells.

In parallel with the stacked, 6-junction cell development, the solar arrays have been designed and prototyped. This has required significant design work since typical solar arrays are based on glass-encapsulated, rigid modules which are not suitable for use on UASs. NRL has established a design for flexible solar arrays that will serve as the topmost layer of the UAS wing skin. Several prototype array structures have been built (Figure 3) and are undergoing testing.

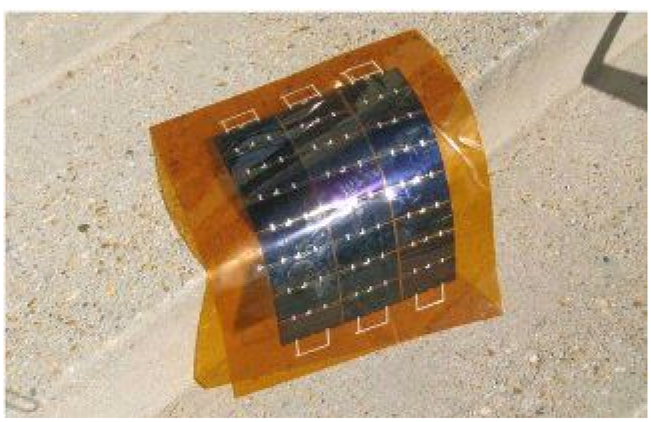

Figure 3: Flexible solar array material being used to develop the UAS wing skin. This example uses multijunction, large-area solar cells with flexible encapsulation.

The GaAs-based, MJ solar cell development continues. As of the end of phase II, NRL has fabricated 3-junction cells based on Gallium Arsenide (GaAs) stacked upon 2-junction cells based on Indium Phosphide (InP). Under 1-sun illumination in the laboratory, these stacked MJ devices achieved 37.6 % (Fig: 5), and we fully expect to exceed 40% within the next 12 months.

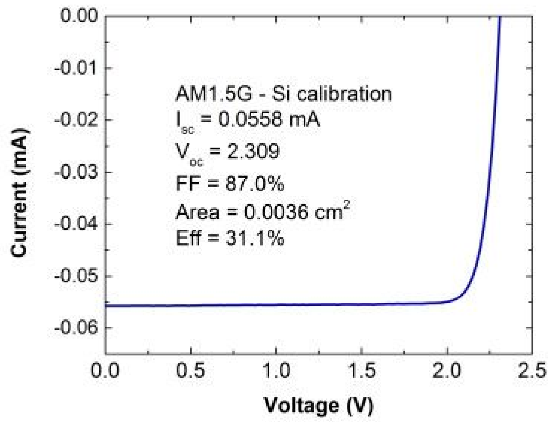

Figure 4: The MJ stacked solar cells under development at NRL have achieved a total of 37.6 % efficiency by stacking two MJ solar cells into a single device. This is a four terminal device, so the top and bottom junctions are measured independently.

As the NRL development of the GaAs/InP based stacked solar cells continues to achieve extremely high efficiency, other flexible solar cell technologies have surfaced that have the potential to provide ~30% efficiency at the cost of a typical Si solar cell. The primary technological breakthrough is the Perovskite material that grows out of the organic solar cells area and has recently achieved efficiencies of about 20%. The focus of the NRL research is to marry the Perovskite and Si technologies to achieve a 30% solar cell. Since new Perovskite layers are made in a solution, they are easily integrated onto the top of an existing Si solar cell, enabling a large boost in efficiency at minimal increase in cost. NRL modeling has developed a novel tandem solar cell design (Figure 5) that will be a focus of near term research.

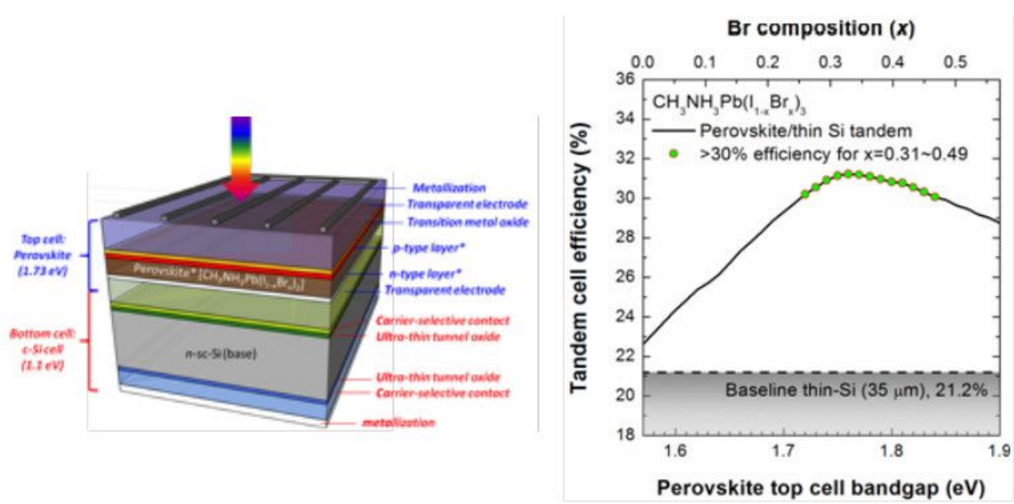

Figure 5: The left hand figure show the schematic diagram of the NRL developed Perovskite/Si tandem solar cell and on the right are NRL modeled results showing the potential of achieving >30% efficiency.

In phase II, NRL continued the development of the solar UAS. NRL purchased commercially available Si solar cells and used a high precision saw to cut the cells into three sections. Using the wing molds that NRL created, full wing sets were fabricated and integrated into the UAS. Two photos of the UAS are shown in Figure 6. It is seen that the wing structure utilizes both full sized and 1/3 sized cells to maximize the available wing area. The combination of the thinner cells and the specialized lamination process allow the solar cells to flex and follow the curvature of the wing without damaging the cells.

Figure 6: These are photos of the UAS with the Si solar cells integrated onto the wing skin. The solar arrays consists of full sized and custom made cells, built at NRL.

Near the end of phase II, NRL executed flight-testing of the UAS with the Si solar cells at the restricted Aberdeen Proving Ground location. The primary purpose of this flight was to test the wing structure before integrating the more expensive cells; however, the MPPT, PMaD, and smart battery were all included in this test. Photos of the launch and landing approach are shown in Figure 7. The total power output was projected at approximately 100W at STC. This aircraft requires approximately 90W power to cruise and even at non-optimal conditions, the solar array provided nearly all of the required power, resulting is significant extension of the battery endurance. For comparison, with the solar arrays disconnected, the battery-only endurance is approximately 4hr. At the 1hr mark of the solar-enabled flight, the battery was at 90%, well below the battery-only discharge rate, which would have been approximately 75%. The flight lasted 1hr 22min and was terminated due to an incoming cold front. Flight data indicates that the aircraft models, which project 18 hours of flight time with the Si cells, match the empirical results. Additional flight tests are planned for phase III.

The Packet Digital power management hardware gave real-time data and managed the power flow. Data is currently being analyzed to verify the power usage during flight and look for any areas of optimization.

Figure 7: Photos of the launch and landing approach of the solar airframe

NRL integration of the high efficiency MJ solar array wings is currently underway. The arrays have been laminated and will be integrated into wings now that a solar wing has successfully been molded using the lower cost Si solar cells. While NRL's UAS and solar wing manufacturing process is not designed for commercial use, lessons learned and technical knowledge will be transferred to Packet Digital for the manufacture of a commercial UAS in North Dakota.

Objective 2: Update Power System to Support Commercial UAS

In phase II, the power electronics for the 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. Figure 8 shows a MPPT tracker using GaN devices.

The maximum power point tracker (MPPT) testing has completed with good results. The only issue that arose was insufficient thermal dissipation. This was due to the small size of the Gallium Nitride FETs and the small board size. A combination of thermal compound and small heatsink was found to alleviate the thermal issues.

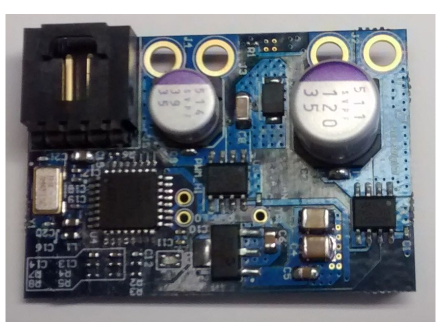

Figure 8: GaN MPPT

The second component in this objective was the design of a smaller form factor power management and distribution (PMAD) board. The original PMAD supported up to six batteries and four MPPTs, which is overkill for many current UAS applications. The smaller PMAD Lite supports one battery and one MPPT. This allowed the PMAD-lite to reduce weight by 25% and size by 50%. The PMAD Lite was flight tested several times and it performed very well. It will be the standard PMAD used until a UAS requires more than one battery or one MPPT.

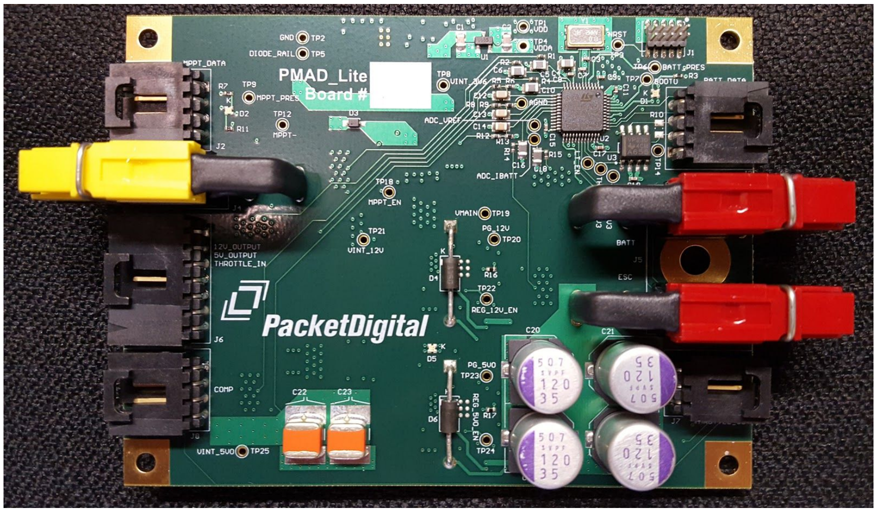

Figure 9: PMAD Lite

The industry comparable aircraft chosen was the Botlink ER-1. It is similar in size and performance to NRL's Airframe. The ER-1 was flown in April at the NP UAS TS for the NASA UTM program. Additional test flights are planned.

Objective 3: Hybrid Smart Battery

During phase II, a new battery technology was made commercially available to UAS enthusiasts. These batteries use graphene to enhance battery performance when compared to a standard LiPo battery. The advantages are listed below.

Advantages of Graphene LiPo Batteries over a standard LiPo Battery:

- Lower internal impedance
- Higher charge/discharge rate
- Cooler operating temperature
- Longer cycle life

The smart battery from phase I was modified to create a hybrid smart battery by replacing one of the six lithium subpacks with a graphene LiPo subpack. This results in a 50% reduction in total impedance, at the expense of a 10% reduction in total capacity. This reduction in total impedance is critical for low-temperature environments, when lithium ion impedance increases significantly. This can be an issue for glider-type UASs that have propulsion systems optimized for cruise at the expense of takeoff performance.

Figure 10: Graphene Battery Pack

A stand-alone version of the smart battery monitor was also developed that will enable key battery parameters to be measured. This battery monitor can be placed inline with a 3S, 4S, or 6S LiPo battery pack. Data is available over an I2C communication bus and includes the following measurements: individual cell voltage, current throughput, coulomb count, temperature, and hardware protection alarms (overcurrent, short circuit, overvoltage, undervoltage. The entire unit is very compact and weighs 27 grams. Figure 11 shows the inline battery monitor alone and Figure 12 shows it connected to a 3S LiPo pack.

Figure 11: Inline Battery Monitor

Figure 12: Inline Battery Monitor with Battery Pack

The phase II hybrid smart battery objective also included research on hydrogen fuel cell technology for UAS applications. Hydrogen fuel cells have a very high energy density, but also environmentally friendly as their byproduct are only electricity, heat and water vapor. A comparison of hydrogen fuel cell energy density to various battery chemistries is shown in Figure 13. 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.

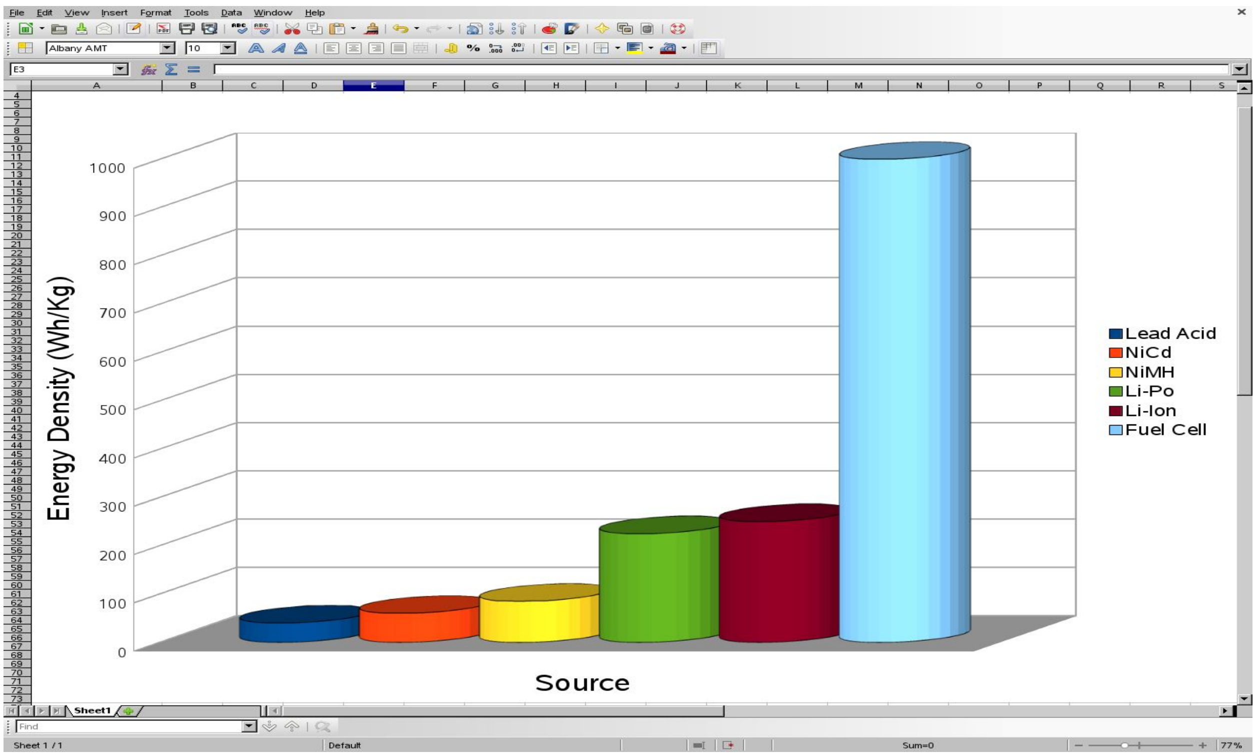

Figure 13: Fuel cell energy density comparison

Discussions were held with the leading UAS fuel cell providers. Fuel cells are available in the 200W-1000W power levels with gas, liquid, and solid fuel technologies. The cost of fuel cells remain rather high for the tightly integrated systems required for a UAS. A full fuel cell system would cost >$30k and requires a supply of high grade hydrogen and a refill station.

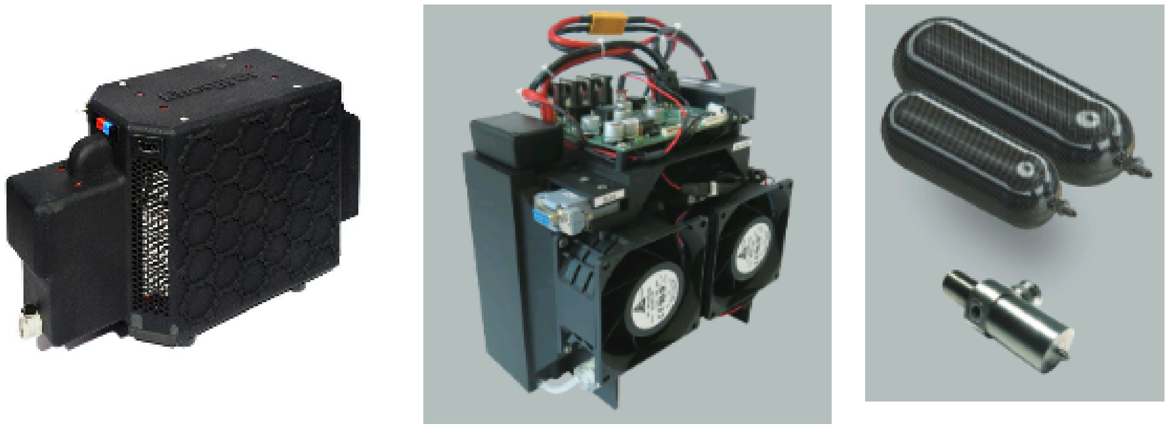

Figure 14: UAS Compatible Fuel Cells

A system which integrates a fuel cell and battery has been defined and simulations have been run.This includes scenarios in which power is extracted directly from the fuel cell, as well as using excess fuel cell power to charge the battery.

Objective 4: Optimized Torque Motor Control

The design of the optimized torque motor control, also known as an electronic speed control (ESC) was completed. The final module is shown in Figure 15. The board dimensions are 43mm x 30mm and total weight, including wires is 44 gram. It is capable of up to 6S input and 20A maximum motor current. The ESC is based on a power application controller shown in Figure 16. This controller includes an ARM microcontroller core as well as the integrated gate drivers and other circuitry required for advanced motor control. The controller also includes firmware for the control algorithms. This advanced controller requires tuning for a specific motor in order to implement the algorithm properly.

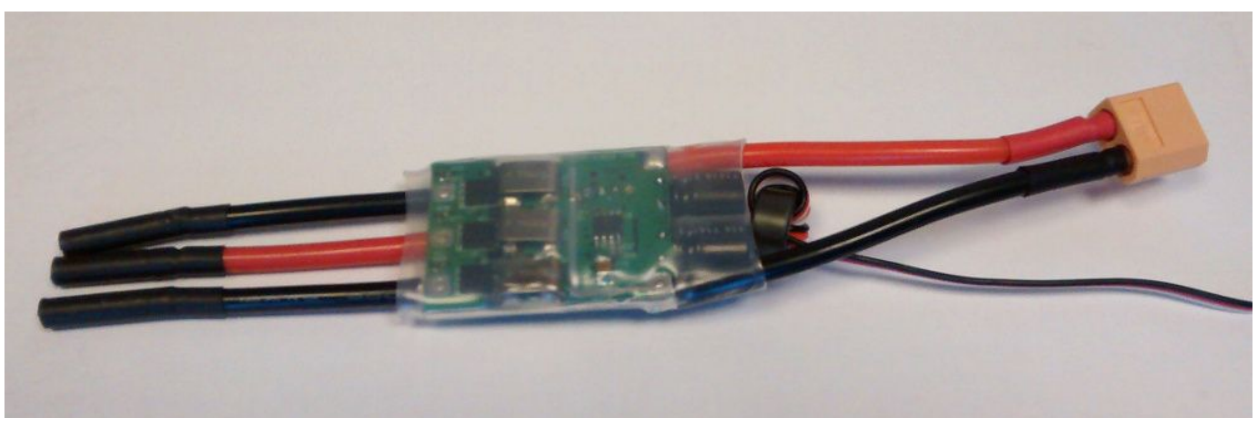

Figure 15: Final ESC Module

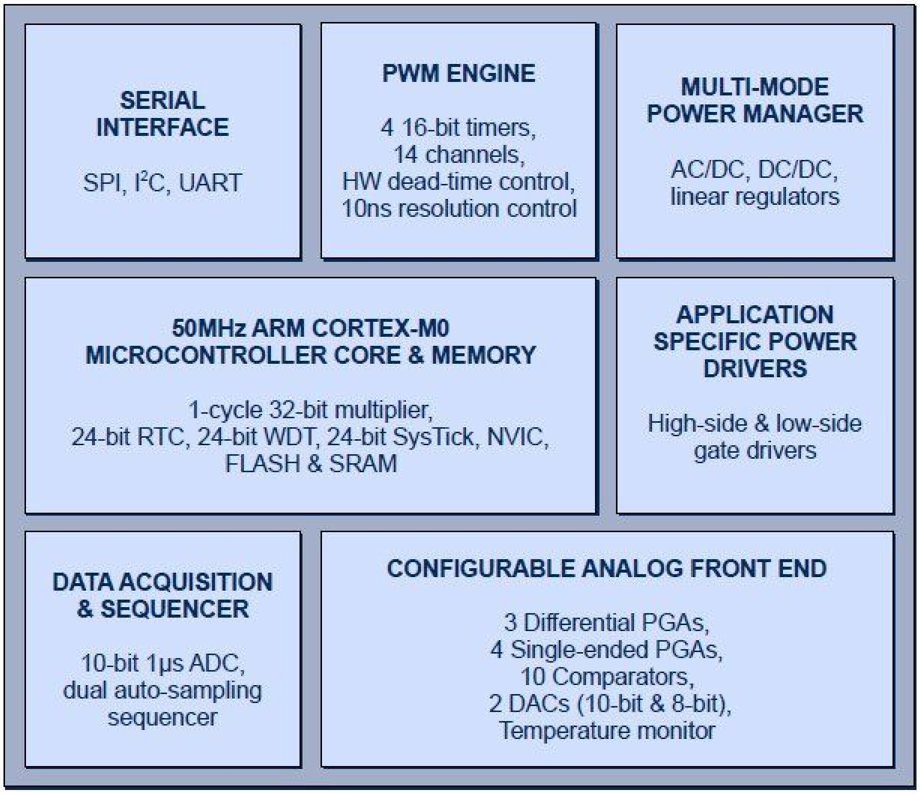

Figure 16: Power Application Controller

The ESC prototype was benchmarked against the of the shelf solution Castle Creations HV Edge Lite 40A controller. All tests were performed using the Neu 1110 motor and 13x11 graupner folding propeller as the load with a source voltage of 22.2V supplied from a BK Precision 9117 3000W programmable DC power supply. There was 12 different configurations for PWM frequency and motor timing advance settings used in the Castle controller. The following table lists the configurations. Each configuration was given 3 runs on an automated static thrust test stand and the results averaged together. The custom ESC prototype does not have configurable ESC timing advance options but relies instead on the measured resistance and inductance of the motor to determine optimum commutation timing.

Config	PWM Frequency	ESC timing	Avg Max Thrust
1	8kHz	0	1304.00
2	8kHz	5	1317.83
3	8kHz	10	1340.67
4	12kHz	0	1315.50
5	12kHz	5	1327.50
6	12kHz	10	1316.50
7	16kHz	0	1335.33
8	16kHz	5	1315.33

9	16kHz	10	1351.50
10	24kHz	0	1327.50
11	24kHz	5	1334.67
12	24kHz	10	1313.50
Prototype	30kHz	-	1275.50

Figure 17: Average Max Thrust Table

The chart below illustrates the amount of static thrust produced for a given ESC throttle input. This illustrates the linearity and maximum thrust available for each configuration.

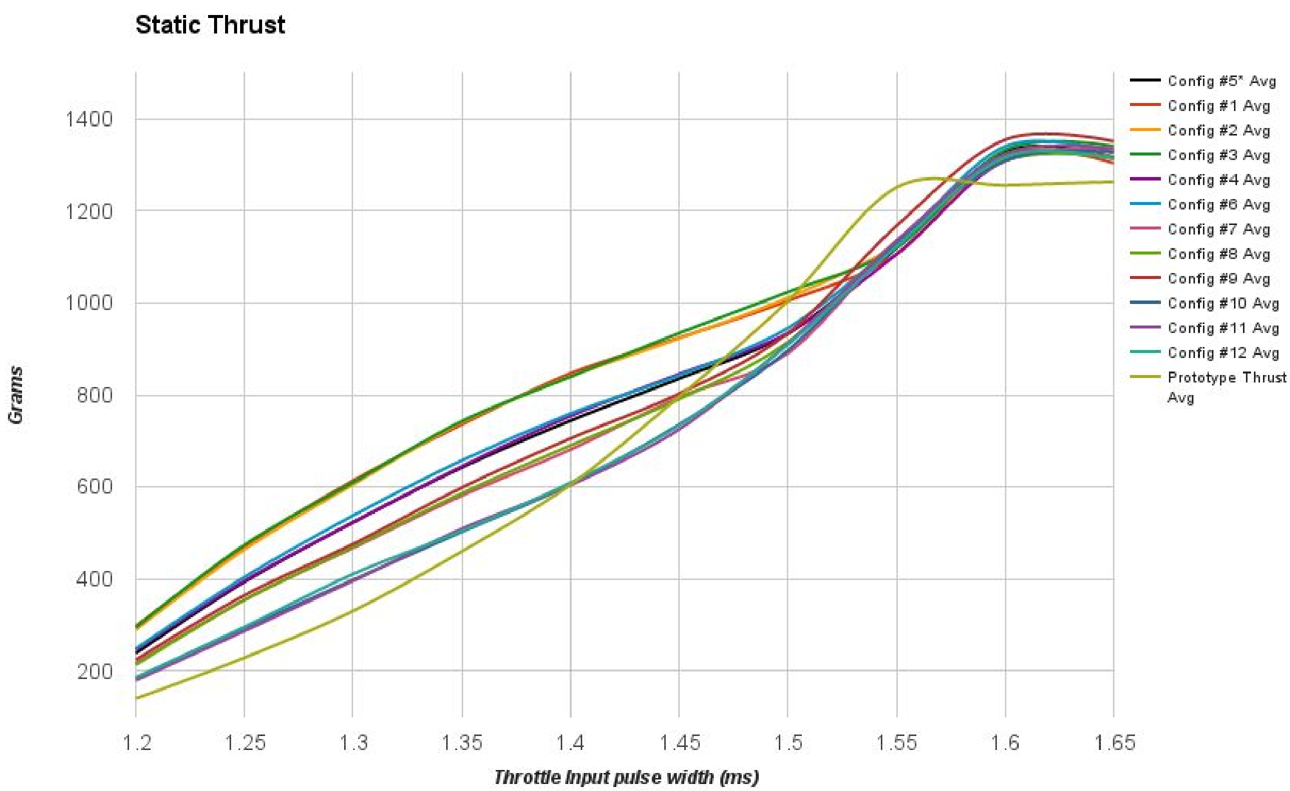

Figure 18: Static Thrust by ESC Configuration

Each configuration was compared for thrust efficiency. Thrust efficiency is the amount of thrust in grams produced for a given watt of power supplied to the motor. A higher value of g/W indicates a configuration that is able to more efficiently produce thrust. The default factory setting of the Castle controller is configuration 5, denoted with an asterisk and black waveforms.

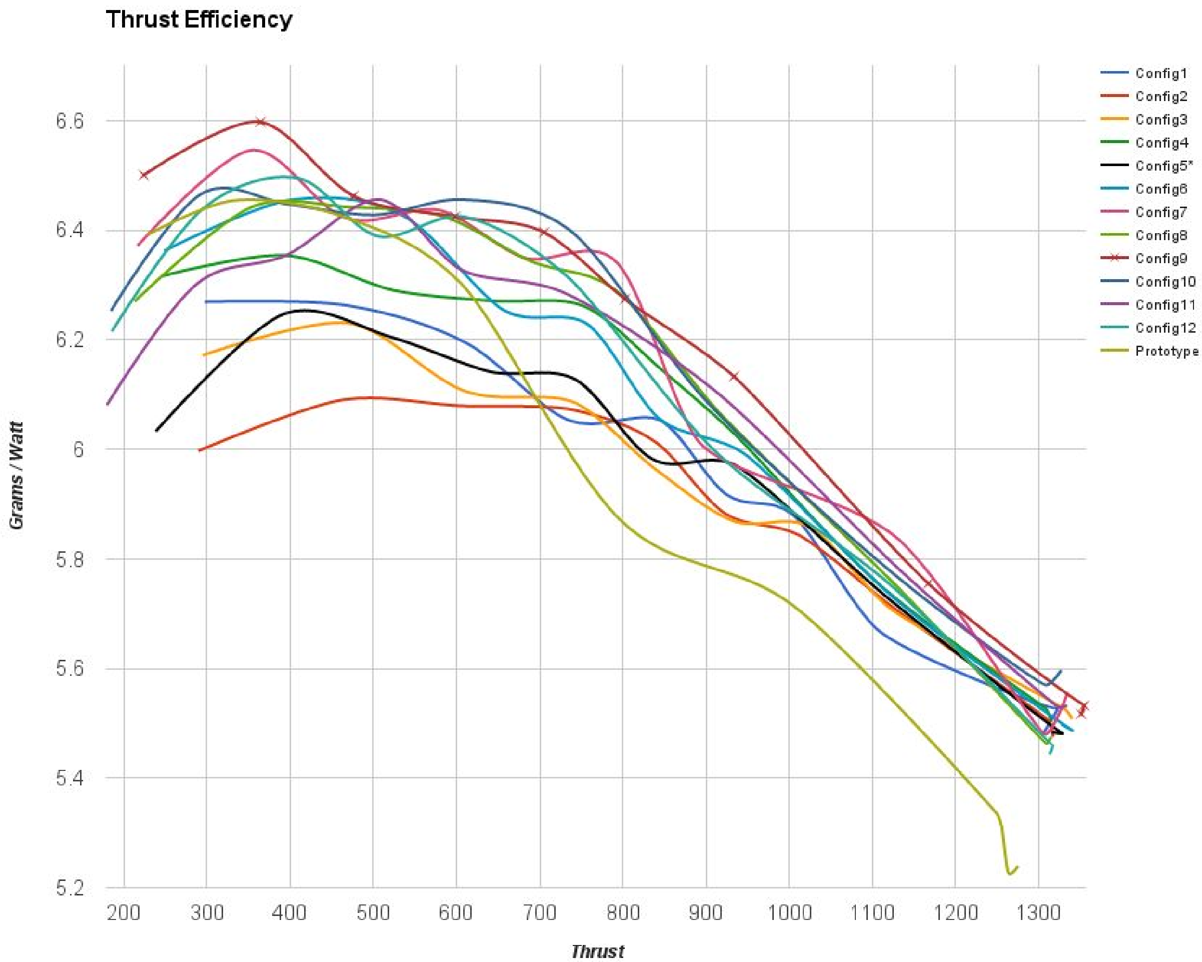

Figure 19: Thrust Efficiency by ESC Configuration

The chart below illustrates the two most efficient configurations versus the default (configuration 5) of the castle creations controller. Testing showed that the Neu motor did not exhibit significant changes in performance with changes in advance timing as the PWM frequency scales upward. Timing advance shows its greatest effect at 8kHz but as the PWM rate is increased the effect is insignificant. As PWM frequency increases the motor exhibits much audibly smoother operation. Performance increases with the 12kHz and 16kHz frequencies but exhibits some performance degradation once 24kHz rate is reached. This is likely to due switching losses in the speed controller starting to become a significant effect but still perform better than the default configuration. The optimized torque controller showed the best performance in terms of smoothness of operation but lacked in terms of performance in the higher speed ranges. While comparable to the best overall configuration 9 in terms of efficiency up to a thrust range of 500 grams of static thrust, the performance degraded above this range. The advanced motor control in tests has shown that performance benefits to be motor specific, that is it may benefit some motors more than others in terms of efficiency based on their resistance/inductance values.

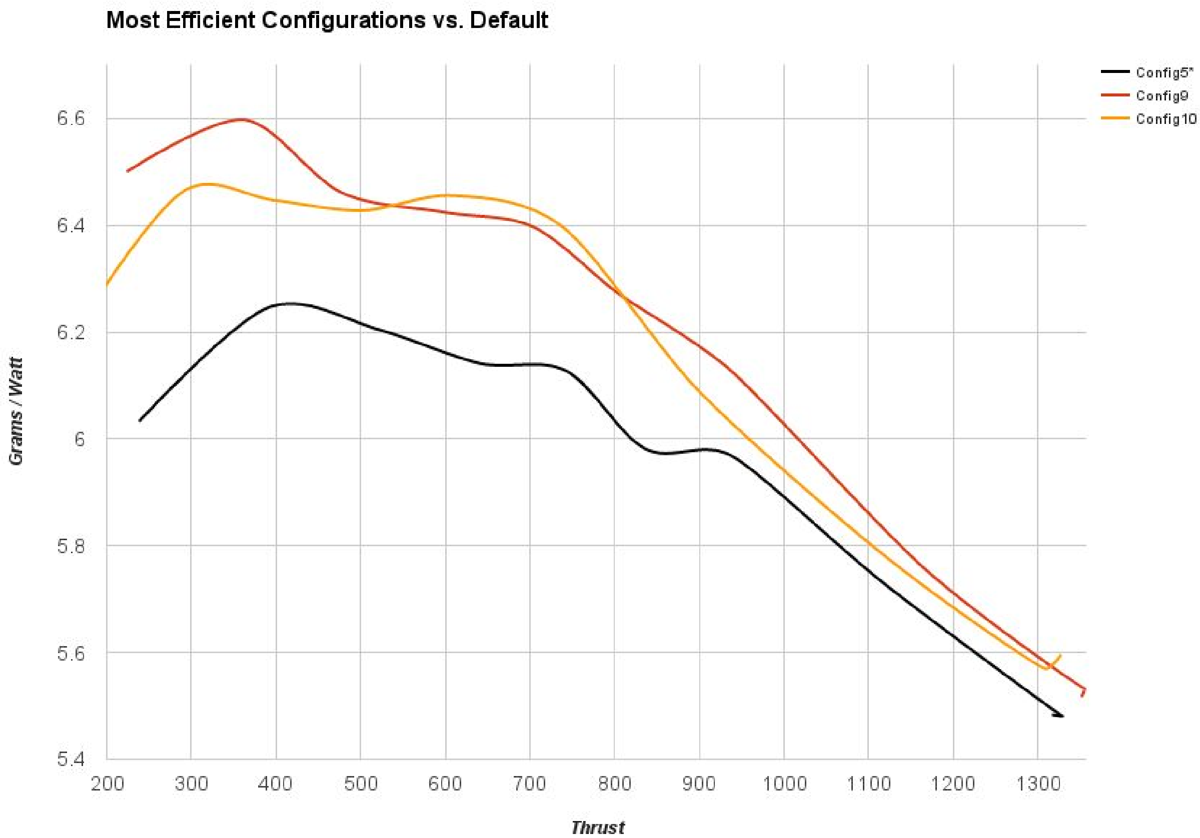

Figure 20: Thrust Efficiency by ESC Config, Most Efficient

Objective 5: Implement Solar Soaring Algorithms

The solar soaring algorithms were originally written in a PC-based numerical analysis environment. This objective translated those algorithms into UAS compatible microprocessor code. The platform targeted was a Xilinx Zynq platform which combines ARM processors with FPGA fabric. Since the Zynq is capable of running a Linux OS as well as RTL, algorithms were written in Python. Once verified in Python, the algorithms can be ported to C code and the Xilinx high level synthesis tools can convert the C code to RTL for execution on the FPGA fabric. A picture of the Xilinx Zynq evaluation boards is shown in Figure 21.

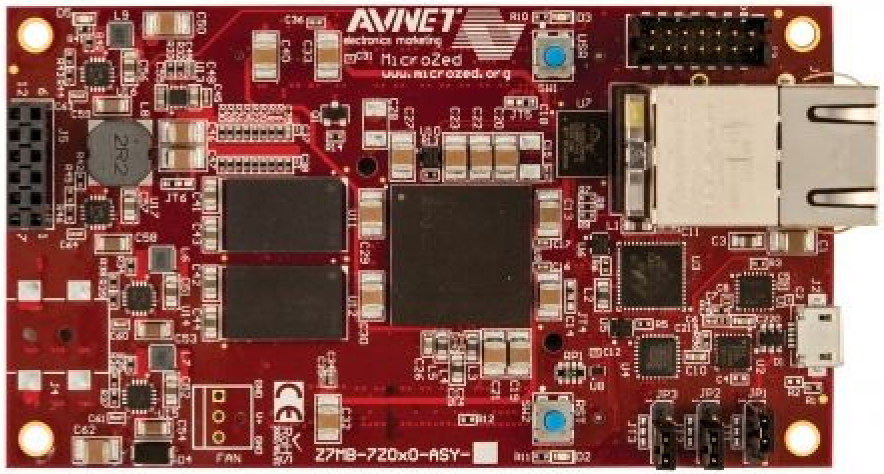

Figure 21: Xilinx Zynq Eval Board

During phase II, Linux was loaded on the Zynq boards and Python code was executed. Algorithms were tested with test data and the performance appears to be sufficient for soaring.

On-board soaring algorithms were flight tested by NRL and the results were similar to that of the PC ground station. Flights occurred during phase II at NRL's restricted test site which allows them to fly at altitudes >1000ft as required for autonomous soaring. This was a significant achievement as it removes the requirement for a dedicated ground station and a proprietary software license. Work on advancing the solar algorithms, including cooperative soaring between multiple UASs is ongoing.

Objective 6: Test All Prototypes

Testing was performed on all new designs. A majority of the testing was done in the lab using the test equipment obtained in phase I of this project.

The GaN MPPT was tested using the solar simulator and source meter. Significant work was done testing various inductor values and switching frequencies. Efficiencies >95% were achieved with proper component selection. Maximum power point tracking worked as expected and matched or exceeded the performance of the phase I MPPT.

The PMAD-Lite was tested both in lab and in flight. Several successful test flights were flown and the PMAD-Lite performed flawlessly.

The graphene hybrid smart battery was bench tested and behaved as expected. It will likely not be flight tested until cold weather flights are performed which require the reduced impedance.

The optimized torque motor control (ESC) has been extensively flight tested in lab using a thrust meter as shown in Figure 22. Test data was included in objective 4 section.

Figure 22: Thrust Measurement Stand

The Zynq soaring algorithm execution unit was tested using test data in software. The tests showed that the algorithm operations were operating correctly. NRL also flight tested and performed further optimization on the onboard autonomous soaring algorithms.

Other activities:

Packet Digital's joint venture company, Botlink LLC, flew at the NPUASTS NASA UTM event this spring in Grand Forks. A non-solar version of the extended endurance UAS was flown successfully. While the goal of this effort was to exercise NASA's UTM concept, it was also an opportunity to test our UAS.

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 June 31, 2016.

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	$0	-	-
Indirect OH and G&A (65%)	$117,800	$0	-	-
Total Personnel Costs	$299,000	$0	$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: Phase II Final Budget

Project Associated Expense	NDIC's Share	Private Sponsor Share	Naval Research Lab Share	Total
Direct Personnel Costs	$212,064	$0	-	-
Indirect OH and G&A (65%)	$137,496	$0	-	-
Total Personnel Costs	$349,560	$0	$542,671	$892,231
Software Costs/Materials	$440	$50,055	$68,334	$118,829
Total	$350,000	$50,055	$611,005	$1,011,060

Summary

Phase II Deliverables:

- Solar cell development
  - GaAs InP MJ cells have achieved 37.6% efficiency under 1 sun illumination.
  - New Perovskite/Si solar cell identified and shows promise of offering 30% efficiency in a low cost manufacturing process.
  - Solar wings constructed and successfully flown, utilizing Packet Digital's MPPT, PMAD, and Smart Battery.
- Update power system to support commercial UAS
  - Smaller, lighter, GaN MPPT has been designed and tested. Efficiency is >95%.
  - Smaller, lighter, PMAD-lite has been designed, tested, and flown. It functions perfectly.
  - The Botlink Extended Range and Data airframe was flown at the North Dakota Test Site as part of the NASA UTM project
- Hybrid smart battery
  - Incorporated graphene LiPo batteries into the current smart battery to reduce impedance while minimizing impact to capacity.

    - UAS-compatible hydrogen fuel cell systems were evaluated and initial design integration with a battery-based system was completed.

- Optimized torque motor control
    - Optimized torque control motor controller (ESC) was designed and tested. Final product is functioning and showing high efficiency.

- Implement solar soaring algorithms
    - Algorithms converted to python code to run on Zynq device.
    - NRL has test flown on-board soaring algorithms successfully.