S.T.E.A.L.T.H
Secure Transmission via Electronic And Laser Technology Hardware

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***Abstract* — In the field of communication, specifically military applications, speed and security are two factors that are not overlooked. These parameters are what our system aims to achieve. The fact that the system utilizes free space optical communication means that you would physically have to intercept the message. For an aerial application that possibility is unlikely. Unlike other communication methods like RF where encryption is a must due to the transmission means, this system does not require encryption and aims to be fast enough to deliver one gigabit of information in one second from system to system.**

***Index Terms* — Lasers, Photodetection Diode, Free Space Optical Transmission, Op-Amp, Buck-Boost Converter, PCB, Serializer, FPGA**

I. INTRODUCTION

In the era of information, the capability to securely transmit and receive information is critical. While many widely adopted wireless communication protocols already exist, such as RF communication, they often require additional layers of security in order to make meet the minimum information security needs of some applications. In such applications, where information security is critical, a directional point-to-point optical communication link can substitute a widely broadcasted channel to greatly reduce risk of signal detection and interception by malicious actors.

While there are use cases for which optical wireless communication (OWC) links have been adapted, there are still many situations requiring a smaller more modular form factor than what is currently commercially available. One such application is on board of small, fixed wing aerial platforms such as UAVs, who often require communication capabilities to facilitate mission requirements.

Our system seeks to fill this need by constraining the self-contained OWC system to have a low Size, Weight, and Power (SWaP) budget with design considerations given towards simplifying pointing and UAV integration requirements. The modularity and mobility of the system that make it UAV friendly additionally poise the system to be potentially adapted easily for other applications that may benefit from a small form factor point to

II. SYSTEM COMPONENTS

Our system by nature is a bidirectional Optical link communication system. The following components are both designed and purchased for our application. Due to either long lead times and component shortages some designed systems were forced to be replaced with bought solutions. The following components were chosen under our core parameters of being light weight, cost effective, and low power.

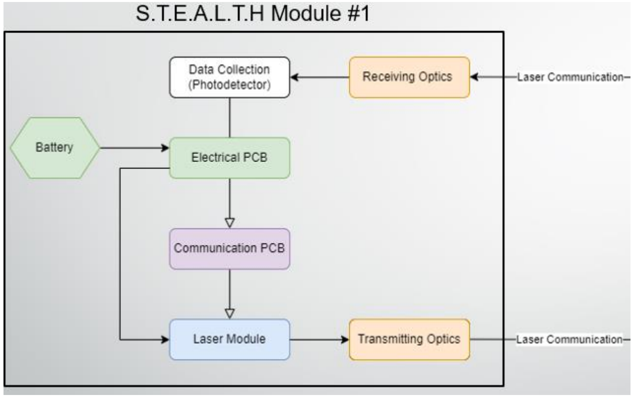

Figure 1. Overall Component Block Diagram

A. *Optical System – Laser*

When trying to select a laser source for this project, some of the primary considerations that had to be made were power, wavelength, and response time. The laser needs to have sufficient power such that a diverged beam at range still has enough irradiance such that enough optical power can be collected by the receiving aperture to support signal recovery.

When comparing wavelengths, two primary motivations were considered: eye safety and atmospheric transmission. A good starting place for wavelength selection was to examine what wavelengths are commonly leveraged by existing optical communications technologies, which also aided in part availability for other project components. For these reasons we chose 1550 nm as our wavelength.

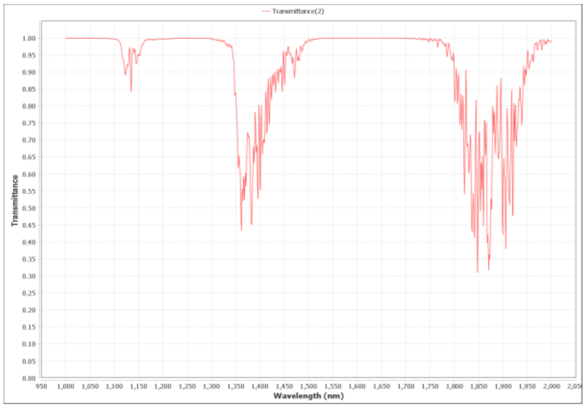

Figure 2. Using the MODTRAN software we confirmed the high atmospheric transmittance of 1550 nm.

The most challenging constraint for laser component sourcing, as well as the sourcing of other components, was speed. In order to be able to reach a potential 1 gbps bit rate, every component within the communication link must be able to operate at a minimum frequency of 1 GHz. For the optical components, this results in needing a response time of 1 ns or less.

The laser that was chosen is the Optilab Distributed Feedback (DFB) 1550-DM-4 fiber laser. It has a 14-pin layout, as seen in Fig. 2. Its operating wavelength is 1550 nm, which is what the project required. The rise and fall times are 100 ps /100 ps respectively. These fall within the limit of 1 ns. The laser operates at 4 GHz analog, or 5GB/s digitally, for the optical transmission link. The peak optical power of this laser is 20 mW.

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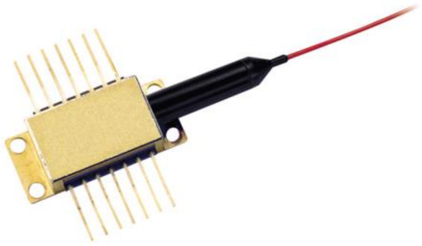


Figure 3. Optilab Distributed Feedback (DFB) 1550-DM-4 fiber laser

B. *Optical System – Photodetector*

The photodetector that was chosen is the Thorlabs DET08C/M - 5 GHz InGaAs Free-Space Photodetector with Window, 800 - 1700 nm, M4 Tap, as seen in Fig. 3. The rise and fall time for this photodetector is 70 ps / 110 ps respectively, which supports a faster than 1 ns response time as required by the target bit rate. The active area is Ø80 µm, which does unfortunately make focal spot alignment difficult. However this device's high responsivity at 1550 nm and fast response time makes it a convenient signal recovery solution for meeting project requirements and objectives.

Figure 4. Thorlabs DET08C/M - 5 GHz InGaAs Free-Space Photodetector

C. *Optical System – Lenses*

The original design for the transmitting optics was an attempt in optimizing a 3-lens divergence controller leveraging the properties of a beam expander with the inclusion of an additional intermediary negative lens to offset the paraxial output of paraxial input rays of the 2f system. This ultimately was less efficient in both volumetric efficiency, on axis stability (more susceptible to platform jitter), and cost to using a fiber collimator to more reliably maintain a small constant divergence. The fiber collimator also has the advantage of being the same price or cheaper depending on the choice of glass optics for the divergence controller.

Figure 5. Fiber Optic Collimator with 0.053 degree ≈ 1 mrad divergence

The fiber collimator selected was chosen based on the goal of having a 1-meter beam radius at a 1-kilometer range, thus requiring a 1/1000, or 1 mrad divergence angle.

On the receiving end, we want to collect as much of light as possible, to compensate for the lowered irradiance at long ranges due to beam divergence. For this reason, we choose to trade some form factor for collecting aperture area, opting for a 2-inch diameter plano-convex lens in order to collect a sufficient amount of light to recover enough signal amplitude for signal recovery. The lens selected is a fast N-SF11 lens with F/1 as seen below in Figure 6. This short ~50mm focal length lens allows the minimum optical train length on the receiving end to be more compact axially, further supporting form factor goals, which further eases pointing requirements for use cases such as UAV integration.

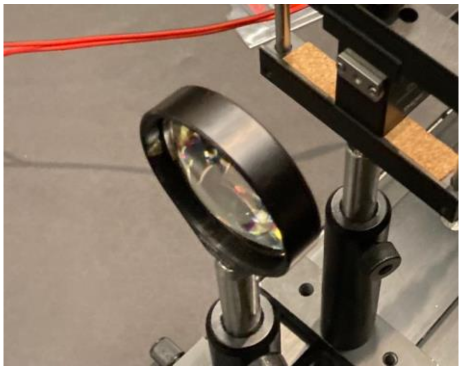


Figure 6. 2-inch N-SF11 collecting aperture

D. Optical System – Spectral Filtering

One inherent challenge a system operating outdoors in the visible or IR spectrums must overcome is ambient optical noise due to solar flux.

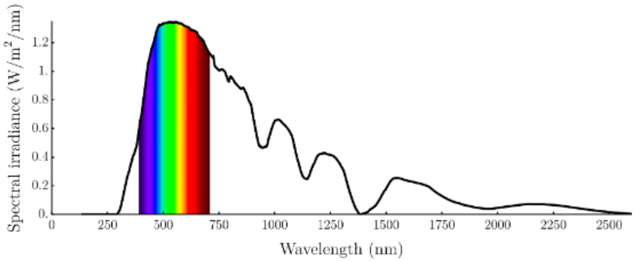


Figure 7. Full spectrum solar irradiance profile

We can model the light scattered within the sensor's field of view as light coming from the sun, hitting a diffuse surface, and scattering in all directions. There are some rays from each spot on the surface that will not make it into the acceptance cone of the collecting lens. The problem can be reduced by concentrating the sum of scattered ambient solar rays as coming from a single on axis point on the surface. We assume that for our diffusely reflective surface, scattered rays originating from it follow an ideal three-dimensional Lambertian reflectance profile whose peak irradiance is normal to the surface. For convenience when thinking about the problem, we will have this diffuse surface subtend the solid angle of the sensor at a familiar distance: the location of the laser transmitter source. The two-dimensional projection of this scenario can be seen illustrated below in Figure X.

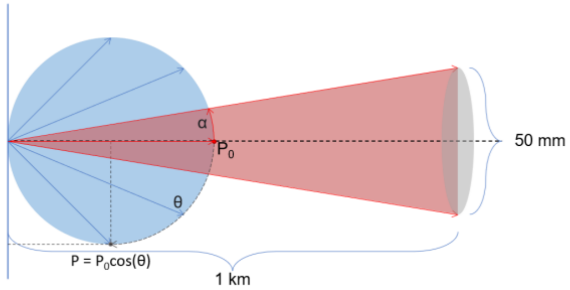


Figure 8. Two-dimensional projection of three-dimensional Lambertian reflection of diffusely scattered solar skylight

From this cone, given a rotationally symmetric system, the percentage of solar flux into the detector from diffusely reflected rays as compared to rays from the direct sunlight case reduces to $\eta_{opt} = P_0 \sin^2(\alpha)$. [1] Across the whole solar spectrum, even with avoidance of direct solar rays, the amount of solar irradiance spectrum within the detector's responsivity wavelength spectrum competes heavily with signal irradiance. resulting in poor Optical Signal to Noise Ratio (OSNR).

The solution to this problem that we have implemented is the inclusion of a narrow band optical bandpass filter centered on 1550 nm. This filter prevents light at wavelengths below 1546 nm and above 1556 nm from reaching the detector. A small half inch filter diameter was chosen to save on cost (narrower band filters are more costly), which by placing it near the focal plane axially still blocks all the out -of-band light being focused onto the collector.

With the Optical Band pass filter in place, the remaining in-band solar irradiance that is expected to make it to the focal spot is approximately 3.67 pW. With this severely mitigated ambient skylight noise, even weak signals at long range should be able to overcome solar flux with good OSNR.

E. *Electrical System – Power*

This section of the system components will focus on the electrical power components of our system. The power delivery circuits are for the laser control and modulation board, as well as the serializer/de-serializer boards. For the laser board requires 5V and 3.5A, most of the current is consumed by the thermoelectric cooler (TEC) as the laser is a sensitive piece of equipment and any temperature variation will increase or decrease the optical output power. The buck converter, TPS54332DDAR, can operate a range of voltages so it met the criteria of being powered by a drone battery. Below is the un-assembled PCB for this circuit. The large traces are both ground planes and power planes as standard smaller planes are at risk of melting.

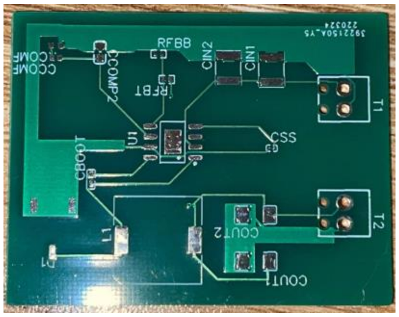


Figure 9. Unassembled Power Supply PCB

The serializer power supply is a lower power supply and mainly for a reference voltage for operating. The buck converter, LM43600PWPR, can also operate at a wide input voltage range making it suitable for this application.

Figure 10. Unassembled Power Supply PCB

F. *Electrical System – Laser Control*

The laser driver and TEC control board is from Modular One Technology. This was a last resort solution to our problem as the laser driver chip from Maxim was not in stock with a unspecified lead time. This board will take our modulated output from our serializer and translate it to a current modulation output to our laser. This board had the added benefit of being able to control our TEC. The designs were completed for that portion but in the effort to reduce cost and overall footprint it was logical to utilize the purchased boards capabilities.

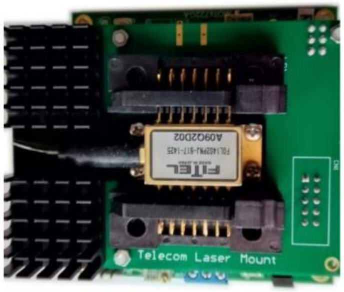


Figure 11. Laser Modulation and TEC Board

G. *Computer System – FPGA*

The S.T.E.A.L.T.H system will have two processing FPGAs, one on the transmitting side of the system and one on the receiving side. The unit in charge of transmission is attached to the laser. It will be fed information that needs to be transmitted through the laser, which will then be received by the other processing unit. The receiving end is attached to the lens. An FPGA development board was procured for the purpose of testing the Cyclone IV’s capability. This development board is shown in the following figure.

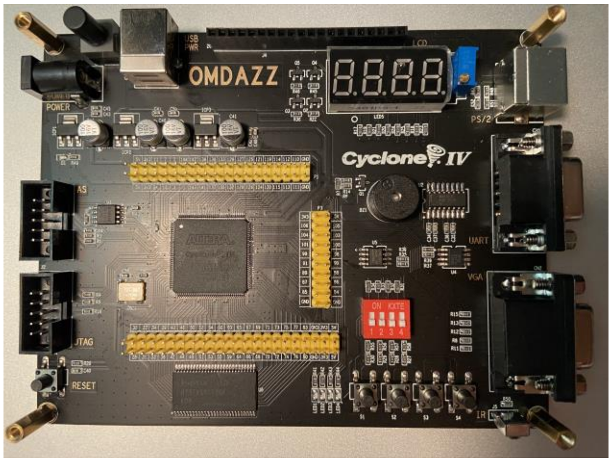


Figure 12. Cyclone IV FPGA Board

H. Computer System – SERDES

One Gbps transmission speeds is the goal for a system like this. The way that such transmissions will be achieved is by incorporating a serializer and de-serializer into the design. The DS92LV2421 and DS92LV2422 are a pair serializer and a de-serializer chips that sends up to 24 bits of parallel data over a serial Bus LVDS link up to 1.28 Gbps.

Figure 13. Assembled Serializer & De-Serializer PCB

III. System Details

Going further in depth into these components the functionality and details of each subsystem will be explained in depth. Each section is dedicated by discipline and logical order of operation to complete a functional system.

A. Optical System – Laser

The 14 pin butterfly mounted laser used in this project had a number of integrated components on board the device including:

- Monitor photodiode (inform laser driver)
- TEC
- Thermistor (inform TEC driver)
- Laser diode (with Bias-T input configuration)

The built-in bias-T circuit especially helped by allowing the laser to be provided a dc bias to reach threshold current independent of the modulation input, which simplified the connection to the modulation signal sources used when prototyping the system.

B. Optical System – Lenses

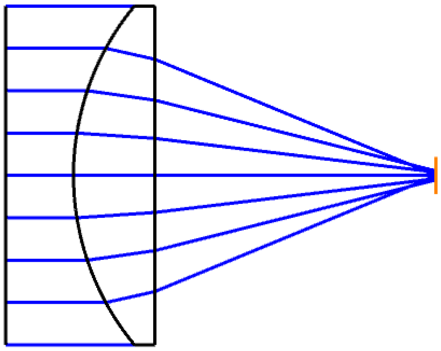


Figure 14. Zemax receiving aperture cross section

Using Zemax, the ideal spacing between the lens and photodetector was found for optimal spot size on the detector active area. The above image does not show the added field for incoming light from the 1 mrad marginal divergence, as light coming from that small angle behaves as if coming from infinity at this scale. This makes the receiving optics convenient to think about, as rays can be treated as coming from infinity at all ranges with sufficient accuracy.

C. Optical System – Optical Link Budget

In any Optical communication work, a link budget is a useful tool for characterizing the amount of expected power at range and analyzing the sources of loss to help in both understanding and mitigating signal loss, as well as predicting OSNR. For this project, a simple link budget analysis was created for 1 km, which was the goal maximum range of the system. Given that most modeling for this project was done under the assumption of a clear day in the central Florida climate, the high transmission yielded from MODtran for that condition was used in estimating atmospheric attenuation ($A_e \approx 1 - T_{atm}$).

Link Budget			
Parameter		Value	dB
Transmit Power (Peak)	P_{tx}	20 mW	13.01 dBm
Divergence	θ_{div}	1mrad	
Link Distance	L	1 km	
Receiving Aperture	D_{rx}	50.8 mm	
Divergence Loss	A_{div}	93.6% @ 1 km	-31.9 dB
Atmospheric extinction	A_e*	0.004345 dB/km	-0.004345 dB
Received Power	P_{rx}	12.899 µW	- 18.894 dBm

Figure 15. Simple link budget analysis which informed signal power and consequently OSNR expectations

The simple link budget analysis shows 12.9 µW of power collected at range. While that number does seem low, when compared to the ambient in band optical noise of 3.7 pW, the system should retain a high OSNR. With a photodetector responsivity of approximately 1 A/W, and a dark current noise of 1.5 nA, even the expected component based SNR when converting to current is still high.

D. Electrical System – Power

The following section will be an in depth look at how the aforementioned PCBs power parameters. First the power supply for the serializer and de-serializer, this PCB requires a small current load so the design is simpler on the PCB end due to the fact that the current traces can afford to be smaller. The total power draw is nominal as the boards require less than 0.1mA to operate. Giving it a power draw of 0.33mW. This board requires an input voltage between 16.5Vdc and 24.5Vdc to operate then the buck converter circuit drops the voltage down to the required 3.3Vdc.

E. Electrical System – Laser Control

The Laser Control board that was designed ended up not performing well for the laser driver itself. The TEC control portion of the board ended up drawing too much power to much current for one of the traces and the buck converter burnt. This was tested twice with poor results for the TEC. The board did however function properly for the laser driver side of the driver board. With the board requiring -5Vdc and +5Vdc the initial design could not meet that requirement. The updated design has the ability to supply both voltages. Due to time constraints this board was purchased premanufactured although I do have a schematical design for this circuit.

A. Computer System

The computer subsystem of S.T.E.A.L.T.H. is made up of the FPGA board and serializer and de-serializer pair. This subsystem is in charge of generating data that will be transmitted over the optical link. After initializing, the serializer begins accepting data from the input parallel pins. The TCLK signal is the input frequency of the serializer block and accepts a frequency between 10 MHz and 75 MHz clock. The serializer transmits 16 bits of data and 2 clock bits (16+2 bits) at 18 times the frequency of TCLK. For example, if TCLK is 60 MHZ, the serial rate will be equal to 1080 Mbps. The De-serializer synchronizes with the serializer input and drives the LOCK pin low to begin delivering data to the ROUT pins.

For the system to transmit data at the desired speed, the minimum frequency should be set to 65 MHz. The FPGA board has a 50 MHz clock that can generate a 65 MHz signal using Intel’s phased locked loop IP core. The serializer requires this clock signal to be sent over the TCLK pin, and 16 bits of data in parallel from the FPGA.

IV. TESTING AND PROTOTYPING

The testing and prototyping phase of our project is a developing section. This section will cover, in depth, everything we have accomplished, and what needs to be accomplished to create a reliable system.

A. Optical System – Laser

Setting up the laser for prototyping was less straight forward than expected, despite understanding the laser specifications well, due to the complicated nature of the laser driver board operation. After properly configuring the board, the driver has enabled a lot of convenience during the prototyping process by interfacing with both the laser diode and TEC in a controlled manor.

B. Optical System – Lenses

This functional prototype houses the receiving end of our optical system. It consists of 2 3-D printed pieces that fit together to properly secure and align the 2-inch focusing lens, as seen in Fig. 16 and Fig. 17. This lens focuses any incoming signal onto the active area of the photo detector. A band pass filter was placed directly in front of the photo detector to block any undesired wavelengths

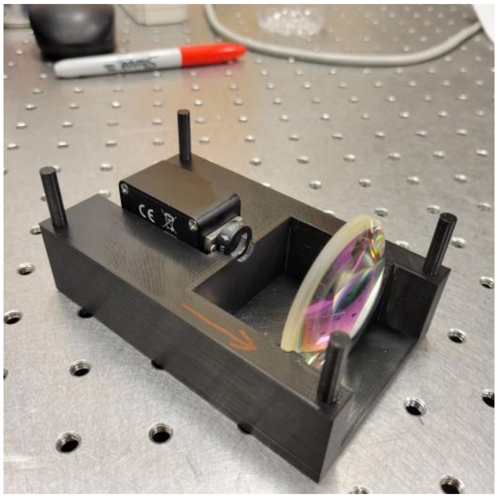


Figure 16. Receiving End Optical System (half assembled)

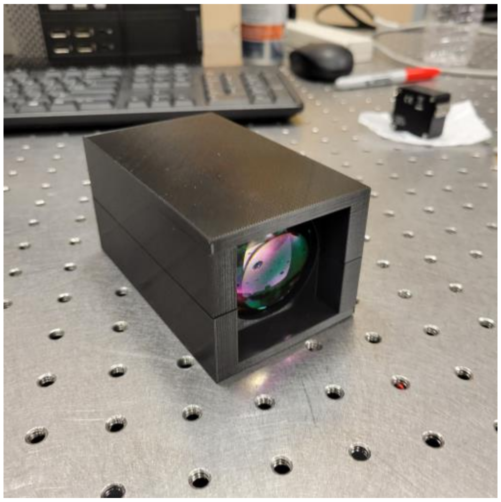


Figure 17. Receiving End Optical System (fully assembled)

C. Electrical System – Power

During testing the boards performed well for the design. Both circuits took in a range of voltages from 16.5Vdc to 24.5Vdc and outputted the required respective voltages. However, the power supply board for the laser driver is not suitable as it can not supply the -5Vdc required for the laser. In testing I connected one board to the +5Vdc TEC connection and ground, then I connected the negative terminal of another board to the -5Vdc

D. Computer System

A working prototype between the two FPGAs established a connection through the serializer and de-serializer. In this prototype, the transmitting FPGA displayed a one second counter on the board's 4-digit 7-segment display. The controls for the display were sent over the serializer and de-serializer to show the counter on the receiving FPGA's 4-digit 7-segment display.

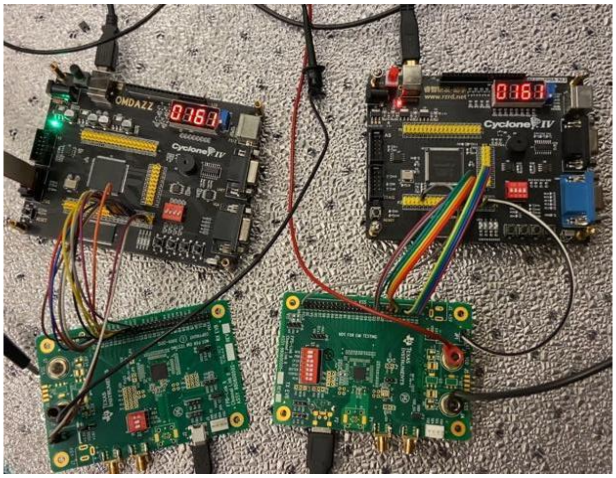


Figure 18. Communication between the transmitting FPGA (right side) and the receiving FPGA (left side)

The next step for testing and further developing this prototype is to design a program that attempts to transmit and receive data using the optical setup.

Using two Arduino boards, another prototype was built which attempted to establish a connection optically to transmit messages. The prototype ultimately was unsuccessful due to the messages not being encoded, producing gibberish signals on the receiving end. After some guidance from a graduate student for the Optics department, the team will attempt to produce successful communication between these two boards by implementing a Cyclic Redundancy Check, which is a way of verifying that data transfers are valid.

V. CONCLUSION

Since the onset of Senior Design, this project's solutions have evolved over time, but the goal has always remained the same since day one: To deliver a compact form factor free space optical communication system prototype. While we have encountered many challenges and stumbling blocks along the way, we believe this has forced us to improve the design further at each hurdle. Even though the prototypes we have created so far are not indicative of a completed optical communication solution, we are confident in the proof of concepts we have delivered to this date at each subsystem level.

During the development of our system prototypes all of our group members have built upon the base of knowledge acquired in our UCF course work that got us to this point. We believe that the inter-disciplinary nature of this project has made all of us more versatile and flexible engineers and has taught us not only how to work with one another, but also learn from one another. We are excited to see what the future potential of S.T.E.A.L.T.H. and the growing free space optics technology space has in store.

ACKNOWLEDGEMENT

The S.T.E.A.L.T.H. team would like to acknowledge the mentorship and financial support of Dr. Kyle Renshaw and the UCF Knight Vision Lab on this project, for which we are immensely thankful.

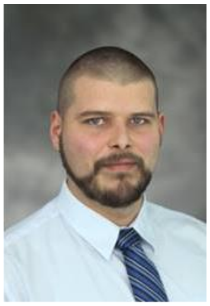
REFERENCES

[1] Nabavi et al. 2020. Dense Visible Light Communication Networks

TEAM BACKGROUND

Austin Brigham Austin Brigham is a senior graduating with his bachelor's degree in Optics and Photonics Science and Engineering. During his time at UCF, Austin has researched for 2 years in Dr. Renshaw's Knight Vision Lab and spent a summer interning for Northrop Grumman. Austin has accepted an offer as a full-time systems engineer at L3Harris in Palm Bay, FL.

Austin Horvath Austin Horvath is a senior graduating with his bachelor's degree in Optics and Photonics Science and Engineering. During his time at UCF, Austin has researched with Dr. Ayman Abouraddy's Muilti-material Optical Fiber Devices Group and then Dr. Kyle Renshaw's Knight Vision Lab group. Austin is currently considering multiple offers in the defense industry.



Wyatt Chancellor Wyatt Chancellor is a senior graduating with his bachelor's degree in Electrical Engineering. During the course of his education, he has been working part-time and full-time, as an Electrical Designer at a consulting engineering firm, where he plans to continue growing his career post-graduation.

Moises Cruz is working towards his Electrical Engineering degree at UCF after having previously earned a degree in Computer Engineering from Penn State Behrend. For the past two years, he has been a part of the College Work Experience Program sponsored by UC and Lockheed Martin. He has accepted an offer for employment after graduation at Northrop Grumman in Baltimore, Maryland.