iSPY

Image ***S***urveillance & ***P***rotection ***Y***ielder

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Chapter 2 – Project Description

2.1 Project Background and Motivation

2.1.1 Background

The history of espionage has always been intertwined to optics and photonics. From the research on lightweight cameras for the U2 surveillance aircraft in the 1940s to the recent creation of unmanned aerial vehicles (UAV) [1], [2]. The need for such technologies guides the direction of present research.

Joe Houston, a SPIE Fellow and past SPIE president highlighted the importance of the innovation in already known systems, “The most covert systems that I know of are those systems – either image communications or electronic communications – that are hidden in the skirts of strong signals in a location that you know, but no one else knows” [1].

Our system, iSPY is then a new chapter of this history. The idea is not to hide the cameras but make the transmission of their captured video something untraceable and uncrackable.

Just like many other technologies that were once created having the military in mind, we hope that iSPY can make its way to the everyday market and bring safety to civilian users of surveillance systems since security is a priority in our daily life. Whether you are a homeowner, a soldier, or a first responder, having eyes on the place you want to protect is a necessity. To prevent crimes from happening, save lives during emergency situations, or to reduce the reaction time if an incident does take place, surveillance systems are widely used.

These surveillance systems usually consist of several cameras that capture live footage of their surroundings. The footage is then transmitted to a device(s), via cable or radio, to display a real-time video of the observed location or objects.

2.1.2 Motivation

Due to the rise of crime, the need for surveillance systems has increased. And unfortunately, these technologies, when poorly used, can lead to more safety issues. Several news outlets have reported the hacking of camera systems [3], [4]. The issue is not only in home security systems, but it is a subject of international security as reported by Scott Ikeda from CPO Magazine. He wrote on Russian military attaining crucial information related to landscape of cities by hacking into cameras Ukrainian citizens used in their homes and businesses [5].

Most security systems are connected through Wi-Fi, which unfortunately, is the most common path for hackers. One of the shared tips on how to secure these devices is to disconnect them from the internet [6]. However, another problem arises with this measure, data transfer cannot take place without Wi-Fi or other means of radio communication.

In iSPY, the need for Wi-Fi or radio signal is to be replaced by a free-space optical (FSO) communication system, eliminating the security risk associated with using Wi-Fi or other radio connection. Since data will be transmitted through light, it will have some features that will make it more secure than the alternative version. One of them is proximity. Light diffracts much less than radio signals, making it hard for an outside entity to tap into the signal being transmitted. Without access to the area where the light is shone it is impossible to access the information. Another attribute of the system is that the receiver's detector is designed and tuned for that specific transmitted signal, the detector is unique to that system, decreasing and almost eliminating the chances of someone matching the specifications needed to decode the data.

2.2 Commercial Technologies and Existing Projects

2.2.1 Koruza

Koruza is a wireless optical internet-access system that advertises the secure transmission of data and easy installation process. A product on the market that matches some of the goals we want to achieve with iSPY. They are also the only open-source free space optical system available.

The system was designed to facilitate data transfer in environments where other options (wireless and fiber optics) are not feasible solutions. Koruza is also easily upgraded, as they say, it is "future proof" [7], [8].

2.2.2 MOSTCOM

MOSTCOM is a well-established Russian company that specializes in free-space optics research and development on earth and space. They have a product line that includes stationary optical systems (OGS), ground-to-space terminals, and mobile terminals. Their current research is on underwater communication terminals [9].

2.2.3 Drone Mounted Object Detection & Recognition using ML and IR Sensors

This was a previous senior design project from a group based out of the University of Central Florida in Spring 2023. This effort combined the ideas of artificial intelligence (AI) and unmanned aerial vehicles to create an autonomous object detection drone. The primary goal for this project was to create a drone-mountable object detection system enabling artificial intelligent visual navigation. The secondary goal was to develop and integrate autonomous peripherals for the drone. The need for this sort of drone technology is widespread for the defense, emergency response, and agriculture industries. The idea, combined goals, and industries of interest of this project are very relevant for iSPY and must be considered closely.

Without knowledge of this project, iSPY intends to build on and design around the successes of this previous collaboration. For example, one of iSPY's stretch goals is the integration of an object detection and free-space optical communication systems on to a drone. Since iSPY is a surveillance system, object detection through computer vision increases the amount of information made available for the end user's discretion. In defense situations, drone-mounted, AI-assisted object detection systems can be employed to detect guns, explosives, or enemy targets in a region of interest. In emergency situations like a wildfire, a version of the drone-mounted, AI assisted object detection system could be used to detect trapped people through the foliage. In agriculture, another version of the AI-assisted system could be used to detect pests amongst crops like groundhogs or certain weeds. It's important to note that iSPY doesn't plan to use a drone to demonstrate AI-assisted object detection; however, it's a stretch goal the team is considering if time permits.

The main difference between iSPY and this previous collaboration is the means of communication with the end user. One of the main motivations for iSPY is to implement free-space optical communication as a means of limiting outsider interference to the signal. If surveillance is to be achieved in secret, then a wire or radio signal cannot be used. Instead, an optically confined light pulse is employed. To interfere, or tap, the signal, the optical must be physically intercepted, making the intrusion known.

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

The project was a previous senior design project from a group at the University of Central in Spring 2022. The project focused on a bidirectional Optical link communication system which utilizes the transmission of data and receiving of said data. In this project the goal was to make the optical wireless communication system more modular and mobile as well as focusing on low size, weight plus power budget within reason.

S.T.E.A.L.T.H. used two different PCB's. One of the PCB's was for serializing and the other was for de-serializing. The design of iSPY intends to utilize a similar transmission of data except without serialization and de-serialization PCB's. Instead iSPY will be using FSO transmission which sends data via digital signal through free space and not an optical link or through PCB's that encode/decode the data.

2.3 Goals and Objectives

The main idea of this project is to build a secure communication, computer-vision-capable object detection surveillance system. A working iSPY device will relay a real-time surveillance video feed to a display by means of FSO. A product of this caliber has the capacity to support defense, emergency response, and agriculture industries, by yielding the end user valuable information for their discretion and mission. The basic, advanced, and stretch goals and objectives for this project are outlined below.

2.3.1 Basic Goals

For this project to be considered "working under basic principles" includes the achievement of several basic, yet specific goals for each sub-system. The surveillance imaging acquisition sub-system must be capable of generating a faint image of the immediate environment surrounding the sensor. The on-board PCB must effectively house a processing unit, necessary electrical components, power systems, and the necessary connection pins. The FSO sub-system must be able to emit (transmit) and detect (receive) a free-space optical beam without signal information. The computer software must be able to read and process an image to generate an electrical signal. The display must be able to turn on without portraying a surveillance feed. All sub-systems will be mounted on an optical table or optical board to provide an experimental demonstration of the project.

2.3.2 Basic Objectives

To achieve the basic goals for the project the objectives listed below will serve as a guide:

- Generate a continuous-wave or pulsed optical output for FSO sub-system.
- Integrate the imaging sub-system to the processing unit using PCB connections.
- Design a PCB on modeling software that meets the above goals.
- Develop software that can read/write data streams.

2.3.3 Advanced Goals

For this project to be considered "working under advanced principles", several higher-level goals for each sub-system must be met to have a video surveillance system. The image acquisition sub-system must capture a clear image feed using an optical design composed of a series of lenses and a compatible sensor. Capturing a clear image will provide more information for the end user's discretion to use on the field. The on-board PCB must effectively house a processing unit, necessary electrical components, power systems, and the necessary connection pins. The power systems must power on the imaging acquisition system and an external processing board. The pinouts must effectively relay an electrical signal from the imaging acquisition system to the on-PCB processing unit, and electrical signals from the on-PCB processing unit to the external board using connection pins. The FSO sub-system must integrate an optical transceiver and evaluator board. Using the transceiver, the sub-system must be able to transmit a modulated optical signal by beams of a diffracting optical beam. The beam must diffract as such to eliminate the need for a perfectly aligned optical system. The transceiver must detect an optical signal, converting it to a usable current or voltage signal to complete the communications channel. The computer software must achieve object detection of people on still images by means of computer vision, overlay a message, and create a usable electrical signal. The display must be able to display a low-resolution image or video. All sub-systems are to be on the same housing structure – wood frame or printed polymer frame – with a built set built-in distance for the FSO sub-system.

2.3.4 Advanced Objectives

To achieve the advanced goals for the project, the following objectives must be satisfied:

- Identify the signal being generated by the processing unit and transceiver.
- Develop an object detection algorithm aligning with advanced product protocols.
- Integrate opto-electronic systems (transceivers) to effectively achieve FSO.
- Create a wide field of view, continuous image feed imaging sub-system.
- Design a PCB capable of connecting and powering all sub-systems.

2.3.4 Stretch Goals

In an ideal scenario, iSPY would be integrated onto a drone and a mobile communications tower, enabling on-demand, location-focused, weather-hardened, real-time surveillance video feeds for the end-user's discretion. The drone module would house the imaging acquisition system, the video feed object detection and signal processing unit, an electro-opto modulator, and transmission optics. The communications tower module would house the receiver optics, an opto-electro detector with an evaluator board, a decryption processing unit, and a display device.

The working product is then to be modular. It'll be composed of two separate and independent modules working together to achieve video surveillance. Video surveillance is a function of video quality. To manufacture and sell a more holistic surveillance system, decreasing aberrations would give the end user more information for their discretion. To accomplish this, an aberration-corrected optimal lens system that satisfies the spatial constraints set by the sensor will be designed. To achieve sustained high resolution video quality, fast bit-level transmission speeds will be generated with an electro-opto modulator (high speed transceivers) capable of generating gigabit-per-second optical signals. Sufficient bit-level quantization will be encoded onto the system and plenty of built-in redundancy must account for faulty signal transmissions intrinsic of the turbulent channel.

The on-board object detection software will be able to detect objects that resemble people from a live video feed, highlight the object, and overlay an object counter on the video. Making the computer-vision package capable of detecting objects would be equally as powerful. This could be accomplished by training the model with objects beyond those that resemble people. These objects can be packages, weapons, vehicles, or environmental conditions like fire or water. The more information is highlighted to the end-user, the more informed decisions will be made.

Visible light cannot be used across all terrains. If the surveillance capabilities of iSPY are to be necessary in areas with dense foliage, sensitive IR detectors would have to be integrated on the imaging acquisition system mounted on the drone. Furthermore, the computer-vision algorithm enabling object detection will need to be refined to detect “fainter” people-resembling objects.

2.3.5 Stretch Objectives

To achieve this high-level of a product, the following must be met:

- Decrease aberrations using corrective optics and image processing algorithms.
- Design an optimal lens system capable of capturing a high-resolution video feed.
- Increase the field of view of the imaging sub-system.
- Create a transmission and receiver sub-systems with a transceiver, evaluator board, PCB, and processing units.
- Develop an upgrade path for the transceiver to facilitate faster data speeds.
- Integrate a broad-spectrum light source to enable all-terrain surveillance.
- Expand the object detection algorithm to other objects while maximizing computational efficiency.

2.4 Required Specifications

Considering the proposed goals and objectives, the required product specifications are:

Table 2.1. Engineering requirements specifications for the performance and physical features of the envisioned system.

Product requirement	Requirement specification	Unit
The system will capture a wide field of view (horizontal)	≥ 100	Degrees
The system will capture a wide field of view (vertical)	≥ 90	Degrees
The system will produce a high image resolution	720	Progressive scan
The system will be designed for low power consumption	≤ 15	Watts
The system will have a high data transmission rate	≥ 1G	Bits per second
The system will have some latency for processing time	1000	milliseconds
The system will have a large optical link range	≥ 1	Meter
The system will be reliable when detecting people (accuracy)	≥ 75	Percent

The system will be able to detect multiple individuals	3	People

Table 2.2 Engineering requirements specifications for the components that will be used in this project to build the envisioned system.

Component(s)	Parameter	Specifications
Image acquisition system (Camera)	Field of view	100 degrees (horizontally) 90 degrees (vertically)
Computer vision algorithm (MCU)	Accuracy of detection	75%
Transceiver output	Transfer rate	1 Gbps
Photodetector power	Optical power	< -10 dBm
MCU	Clock Speed	16 MHz
Camera sensor	Framerate	30 frames per second
Power Supply (External)	Voltage Output	5V DC regulated
Display	Framerate	30 frames per second

2.5 System Diagrams

The engineering scope of this project is divided amongst hardware and software systems, each working in tandem to make iSPY work.

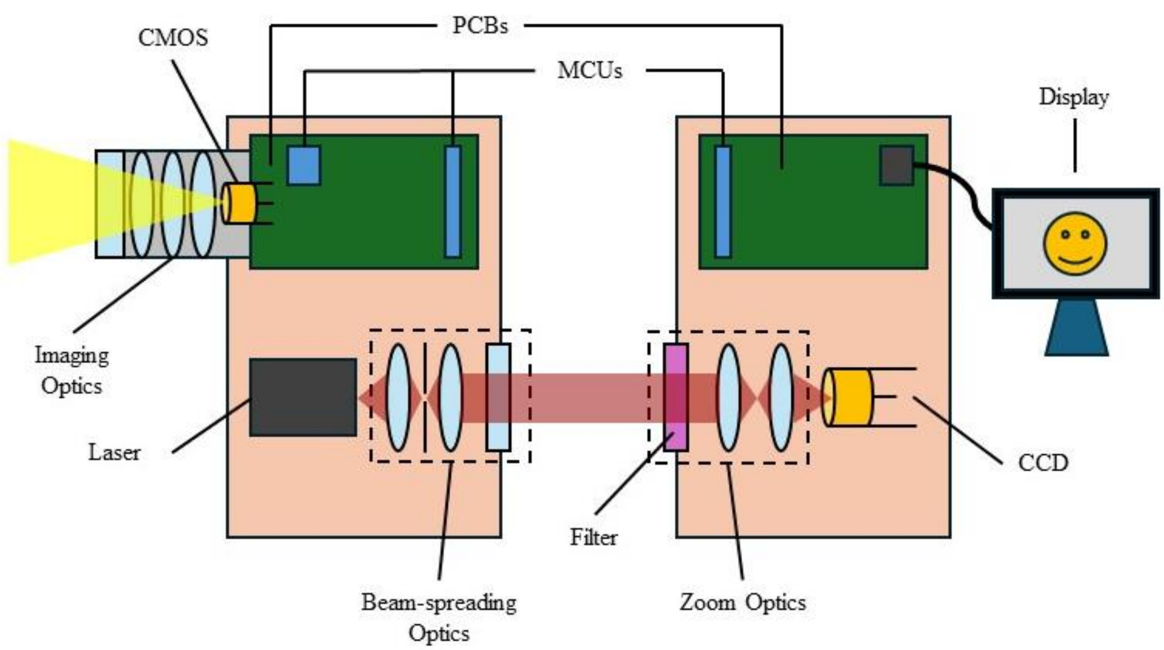


Figure 2.1. *General product diagram by Authors*

2.5.1 Hardware

The hardware is divided into three separate sub-systems: imaging acquisition, free-space optical Tx/Rx, and a display. The hardware layout and separation of work is demonstrated below.

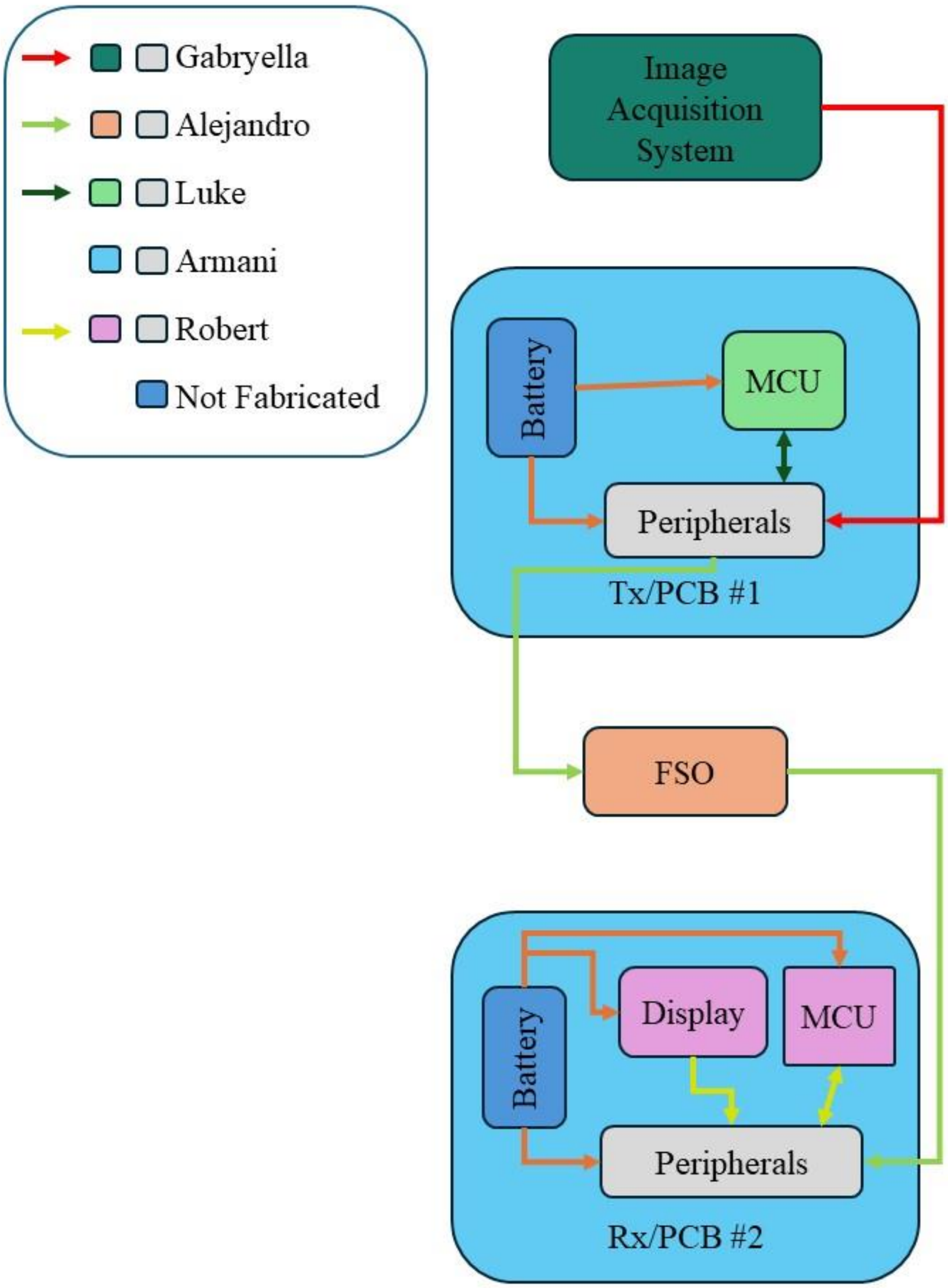


Figure 2.2. *Hardware diagram by Authors*

2.5.1.1 Image Acquisition System

One of the most crucial parameters for surveillance systems is the camera's field of view. Field of view is "is the open, observable area a person can see through their eyes or via an optical device, such as a camera." [10].

The goal with the iSPY is to have a wide field of view without sacrificing too much of the resolution. A wide field of view is needed to capture a large portion of the scene and decrease blind spots. At the same time, high resolution is necessary since the computer vision system will require as much detail as possible to determine what is taking place.

The system will be designed to be placed in spaces where observing a larger portion of the surroundings is more important than seeing "crisp" details. Through computer vision our goal is to be able to tell how many people are in each frame.

This system will consist of an assembly of lenses designed exclusively for this project. The lenses will focus the light, image and correct the observed scenario. The final assembly of these optical components will be mounted to a CMOS sensor forming iSPY's own camera – our image acquisition system.

At the moment, we are leaning towards creating a fisheye lens system since it gives us the most field of view when compared to other systems. When dealing with fisheye lenses, distortions will take place, and through researching and testing we will try to minimize the effect of the distortions and aberrations, optimize the system and change accordingly. Some important points that will play a role when developing this system are the desired field of view (as previously mentioned) which dictates the focal length and the sensor size; the projection type we want to obtain, since we will be mounting it to a sensor; the lenses used for aberration correction; overall lens alignment and sensor compatibility with the rest of the system.

Choosing the different parts of this system, understanding their interaction, and simulating outcomes on Zemax will be the key to obtaining a successful prototype.

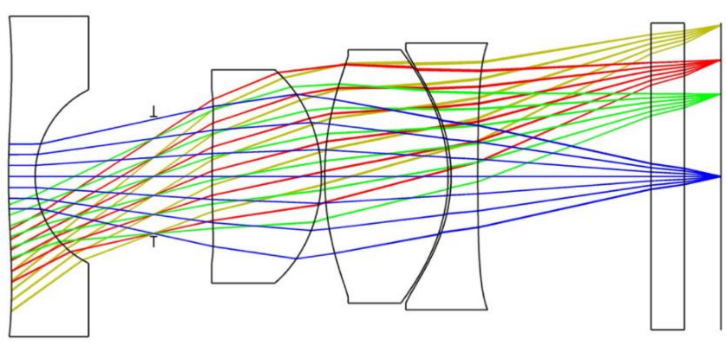


Figure 2.3. *Layout of a wide-lens system from Reference 11. [Permission Requested]*

Figure 2.3 shows the design of a wide-lens system [11]. Wide-lens and fisheye lens systems usually follow a similar structure, and this is what we currently have in mind. Our system will follow industry's frameworks and expand to match the requirements of our design.

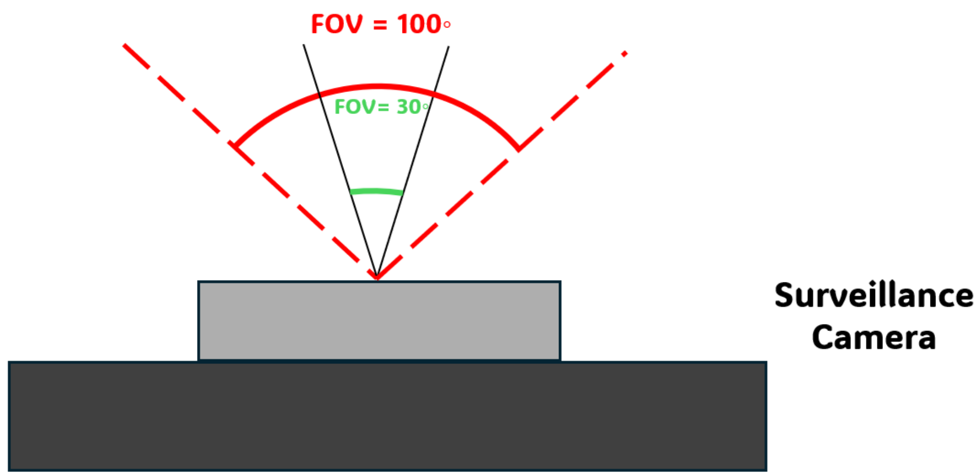


Figure 2.4. *Field of view captured.*

Figure 2.4 shows the field of view, our observed region, we want to accomplish with iSPY. Some cameras can cover the larger region (180 degrees). However, the optics at that point introduce a lot of aberration and for this project, high resolution images (videos) are needed for computer vision. Therefore, we will focus on a smaller portion of the observable area and focus on the quality of the image.

Having the scope of this class in mind and facing some uncertainty due to the cost and size of equipment, our visual monitoring system will consist of only one image detector and the focus will be on capturing live video of a well-lit environment, such as, inside a building and outdoors during daytime. One of our future goals (stretch goals) is to implement the system outside, mount iSPY onto drones and have it running regardless of the time of the day.

2.5.1.2 Free-Space Optical Transceiver System

The backbone of iSPY is its free-space communications capability. The transmission (Tx), receiver (Rx), and FSO systems can be considered sub-systems. The Tx and Rx systems are electronic housing sub-systems, whereas the FSO system is the optical design connecting the Tx and Rx sub-systems. Each is explained in further detail below.

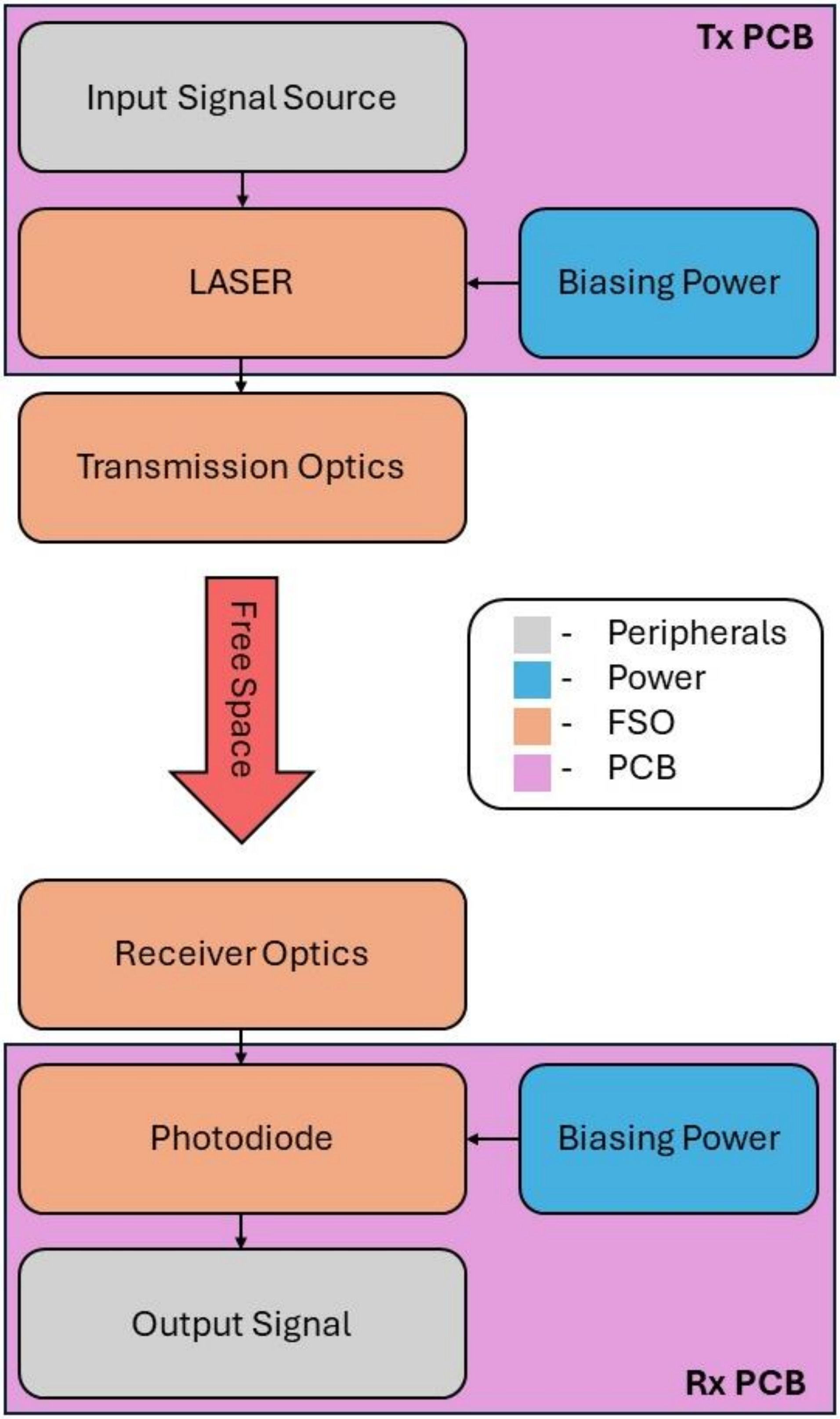


Figure 2.5. *FSO transmission/receiver system diagram.*

2.5.1.2.1 Transmitter Board (PCB #1)

The goal of the Transmitter Board is to utilize the Image Acquisition System that takes a live video feed then uses computer vision recognition to recognize how many people are in the field of view. Once the computer recognizes the amount of people it will send that data to a laser diode by compressing the data into a bitstream. The Transmitter Board will process the video feed using a MCU into a binary sequence that can be broken up into 4 or 8 bits at a time creating this bitstream. The laser diode then can take this bitstream and transfer the data via laser.

As a separate modular entity, this Transmitter Board will need its own MCU and power supply to make sure this process runs smoothly. The MCU chosen will handle the data and signal processing, allowing the data received from the Image Acquisition system to be transmitted by the laser diode in the FSO communication system at the end of this board. This will be done through an amplification circuit to match the MCU's input requirements and signal integrity.

The data received will be processed through binary encoding as it passes through the MCU and in turn form the bitstream that will transfer through the laser diode driver circuit and modulation scheme. The laser diode driver circuit will be designed to modulate laser diode with the bitstream from the MCU, but it will also need a current control loop so that the laser diode will not hit overcurrent conditions.

Power and thermal management is a crucial task within this PCB as there are multiple processes that affect one another. Each major component (image acquisition system, MCU, laser diode) will have its own specific requirements that need to be met, so having low-dropout regulators as well as decoupling capacitators could reduce instability in the system. Signal interference is another concern that can be bypassed through optimizing the trace lengths to reduce signal degradation and the decoupling capacitors and low-dropout regulators. Therefore, the power supplies are very well filtered, and a careful distribution circuit is used to avoid spurious noise and transient coupling among the transmitter and receiver circuits of the transceiver and ensure signal integrity on the printed circuit boards [12].

2.5.1.2.2 FSO Communication System

The success of this project depends on free-space optical communication, the means of data transmission being employed. Unlike other optical communications systems, like optical fiber communications where the means of data transmission is confined in a fiber optic cable, free-space optical communication systems transmit data in free-space, open-air channels. This type of system will not be confined by any conventional means like a copper or fiber optic cable.

The FSO system employed will transmit an intensity modulated quantized bitstream using a LASER-capable semiconductor, also known as a laser diode. To create a workable communications channel, a spatially confined optical signal beam will be achieved using a series of lenses. The optical design of a laser transmission system requires a collimating 4F optical system. A 4F system will enable efficient beam expansion/contraction and beam shaping. Beam expansion/contraction depends on the lens pair of choice, whereas beam shaping depends on the Fourier filter used in the 4F optical system.

To complete the FSO communications link, the transmitted optical signal will be picked up by a sensitive semiconductor optical sensor, also known as a photodiode. The photodiode will convert the received optical signal onto usable electrical signals, making it a critical component of a Tx/Rx optical system. Even though the transmission beam is spatially confined by its degree of divergence, the beam must be captured and imaged onto the surface of the photodiode. Like the transmission system, the receiver side will also employ lenses. The optical design of the receiver makes use of one or two lenses, depending on availability and precision specifications.

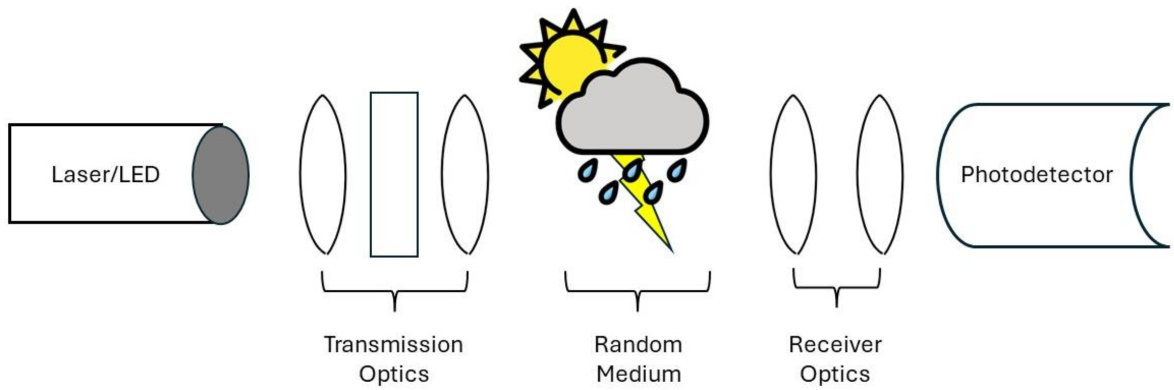


Figure 2.6. *FSO system schematic by authors.*

2.5.1.2.3 Receiver Board (PCB #2)

The goal of the Receiver Board will take the data being received by the photodiode and generate a bitstream. Once a working bitstream for the display is generated then it is sent to a display. For the sake of transparency, this PCB will be purchased prebuilt as per advisor suggestion. On the display it will show the number of people the computer recognized and box them out with a colored outlined box.

For this process to work, the photodiode is essential in this PCB’s input. However, the signal from the photodiode alone would be too weak to perform anything with it, therefore an amplifier circuit will be used to complement the photodiode and boost the signal we receive. This will make it possible to further process that signal. On top of the amplifier, we can add another circuit on the backend whose whole purpose is to ensure signal clarity, filtering out any noise that could taint the desired output.
The main processing unit, our microcontroller (MCU), will take over the functionality of this PCB after the signal is properly amplified. This MCU will handle Analog-to-Digital conversion (ADC) and data processing. The ADC in the MCU will be responsible for converting the analog signal received from the photodiode into a digital component that will be processed by the software programmed onto the MCU. All the data accepted and

processed by the MCU will be stored in temporary memory waiting to be transmitted to the next step of the process.

The output stage of the PCB will have the video data pushed through a display driver circuit which will deliver the video signal to the display, ensuring compatibility with whatever interface we so choose.

To ensure optimization and performance, we will have to have some factors that need to be addressed and taken care of since the Receiver Board is modular but separate entity, there will be a dedicated power supply unit that provides voltage regulation and a protection circuit to keep stability within this PCB. The distribution of power will have to be carefully managed across the board to make sure the components are safe, and the important parts of the system won't get burnt out. Signal integrity is a major issue that would make or break the process since we want clear data that we can work with and get an output from.

2.5.1.3 Display

An external monitor will be used to display the captured and relayed real-time video feed. For the monitor to generate an image, it will be connected to an external power source and a video-out port on the receiver board. The onboard computer will generate the acceptable signal format for the monitor of choice. The signal format will vary between monitor models and video resolution.

2.5.2 Software

The software is divided into two separate sub-systems: object detection processing and digital signal processing for Tx/Rx. The software flowchart and separation of work is demonstrated below.

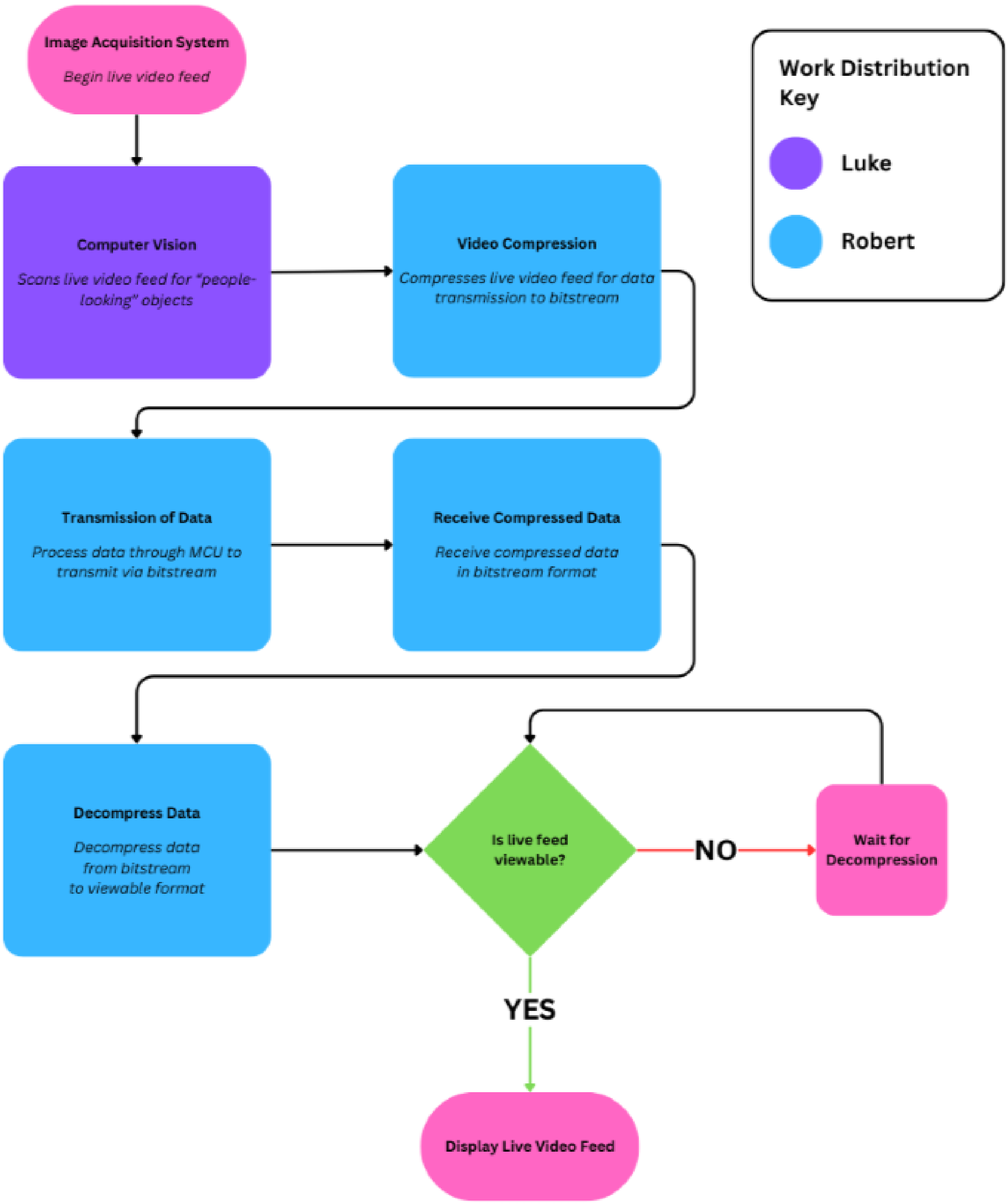


Figure 2.7. *Software diagram by Authors*

2.5.2.1 Object Detection Processing

The goal of the computer vision side of this project is to detect the number of people on the live video transmission at any time. This can be achieved with real-time processing of the live video feed to acquire an accuracy of 75% or more. A suitable approach to attain these kinds of results could be utilizing deep learning. Neural networking with many layers can give our computer vision the ability to understand more complex detection. Examples of this complex detection could include poor lighting, night vision, different angles of the body, and even clothing covering crucial parts of the body for detection. The program would detect the total amount of people in the image and display this number on the output screen so that the viewer of the surveillance system knows exactly how many people are currently on the feed.

Neural networking is a process of machine learning that utilizes a “neural net” of many nodes. These nodes receive data and assign a “weight” to the data received. Each node will pass down this data with the assigned weight to the next node and so on. There is a desired weight set for each node. If the node is under the desired weight, it will not transfer the data. If it is above the desired weight, it will pass on the data. The weight of the data determines how important the information gathered is. Once the data has gone through the entire neural network, it will arrive at the output layer. The output layer is where the result will be displayed. [13]

In this case, the program is attempting to recognize human bodies in a live video feed. The program will almost certainly not output an accurate result on the first attempt. That is where the process of training comes in. Neural networking will be used and the best attempts from previous runs will be remembered. The program will remember the previous data and use it as comparison when going through the neural network in future runs. This process will repeat until the program can accurately detect a human body 75% of the time.

2.5.2.2 Digital Signal Processing for Tx/Rx

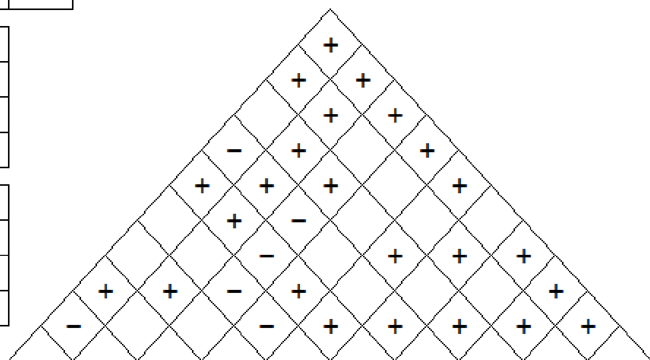
The image acquisition system will relay a live video feed processed by the computer vision algorithm which recognizes an object as a body. Once the process of recognition is done then another algorithm will compress the data into a bitstream which is sent to laser diode as a digital signal. The photodiode will receive this digital signal as an optical signal and convert it to a digital signal. The MCU will decode the digital signal into a working bitstream for the display.

2.6 House of Quality

Correlations		Weight
Strong	●	9
Moderate	○	3
Weak	▽	1

Relationships	
Positive	+
Negative	−
No Correlation	

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



Column #	1	2	3	4	5	6	7	8	9	10
Direction of Desirability	◇	▲	◇	▲	◇	◇	▲	◇	◇	▲
Engineering Requirements / Marketing Requirements (Explicit and Implicit)	Image Resolution	Image Processing Performance	Object Detection Performance	Optical Power Received	Optical Link Range	Power Consumption	Transmission Speeds	Latency	Display Resolution	Usability
Affordability	●	●	▽	○	●	▽	●	▽	●	●
Reliability	●	●	●	●	●	▽	○	●	●	●
Connectivity/Easy to Setup	▽	▽	○	●	●	▽	○	●	●	●
Communication Range	●	○	●	●	●	○	▽	▽	▽	▽
Fast Transmission	●	●	▽	●	●	▽	●	●	●	▽
Standard Quality Video	●	●	▽	●	●	●	●	●	●	○
Secure	▽	▽	▽	▽	●	▽	▽	●	▽	●
Versatility	●	●	●	●	●	●	●	●	●	●
Relative Weights	56	50	34	58	72	26	44	56	56	50
Product Targets	720p	30 fps	≥ 75%	< -10 dBm	≥ 1 m	< 15 W	≥1Gbps	1 sec.	720p	Adaptable

Figure 2.8. *House of Quality*

Chapter 3 – Research

3.1 Sensor parameters

The first step on building iSPY was choosing the camera sensor. The camera sensor would dictate what kind of signal and video format we would be provided to the rest of the system.

Choosing the sensor is the first step in many optical design projects because there is a standard to be followed. They are usually not custom made, and especially for a project like ours it would be impossible to design and fabricate one. However, there is freedom for lens choices. Therefore, we followed the steps of other optical engineers and decided to work around a sensor. [14]

When choosing a camera sensor one of the most important parameters is its size. There are so many options, and each choice comes with a tradeoff. Understanding what is important for our system is key. To make sure all parameters were considered ChatGPT was used to point out the main factors to look out for when choosing a sensor. The parameters were: Sensor size, resolution, frame rate, dynamic range, shutter type, data interface compatible with the system, etc. I also integrated other parameters to the discussion like crop factor, depth of field, F-number, image circle.

Sensor format size is the starting point when choosing a sensor. It dictates nearly all operational metrics of the imaging system. [15] An equation that shows this strong relationship between sensor size and the parameters are:

$$\text{FOV (in degrees)} = 2\ \tan^{-1}\left(\frac{w/2}{f}\right) \text{ [Eq. 1]}$$

Where f is the focal length and w is the sensor width [16].

For our system (and surveillance system in general), a wide field of view is crucial.

Field of view (FOV) is an angle measurement of how much of a scene is visible to a device or human like previously mentioned. It is the parameter that lets the viewer know how they can see. For this project, when referring to field of view we will be strictly talking about the camera's FOV unless mentioned otherwise.

With equation 1 in mind, we can see that a larger sensor will increase the field of view.

Other benefits of a larger sensor are that it decreases diffraction, gathers more light, in other words, it acquires more information increasing the quality of the electrical signal that is converted by the pixels and having better performance in lowlight environments. [17] [18]

The downside of a large sensor is its size, with a larger sensor we also need larger and consequently heavier lenses. The price also increases dramatically [17] [19].

However, an important feature is that for sensors designated for video recording/streaming increasing the size of the sensor does not add too much to the system, it is not a clear linear relationship like it is for photography. A larger sensor should only be considered in specific cases like extremely shallow or deep depth of field and shooting low-light performance [17].

If the aperture is to remain the same, something we have to take into consideration because in this project that is the case, the depth of field (range of distances where the images are clear) will decrease as the size of the sensor increases. The way to counterattack this effect would be to get closer to the subject of to increase the focal length to fill the frame. However, both options are nonviable in our system. The camera will not move closer to a subject and the focal length will not change [19]. So even though larger sensors will provide greater detail, depth of field is not something a surveillance system can tradeoff.

The F-number (f/#) or f-stop indicates how much light passes through a lens and/or optical system. It is the ratio between the focal length and aperture diameter.

Low F-numbers are related to large apertures, more light enters through a lens and the system is great in low light conditions. Lenses with a low F-number are called fast lenses.

High F-numbers, on the other hand, describe small apertures, where less light comes into the system and are best used in well-lit places. They also have a greater depth of field than low F-numbers. Lenses with a high F-number are called slow lenses.

Since the security we want to build will be used during the daytime and inside well-lit places, lenses with low F-number are not needed. And this also decreases the cost of our system since moderate to high F-number lenses are cheaper.

Moderate F-number lenses were previously mentioned because it is a trade-off that needs to take place to decrease diffraction. A really high F-number is not ideal.

Another crucial parameter equation 1 displays is the relationship between focal length and field of view. We will go into more detail about focal length and effective focal length of the system in the second part of this second where we explore lenses, but even now we see that a short focal length will increase our field of view.

Resolution can be defined as "the dimension of the finest spatial detail in the object that can be discerned in the acquired image." [22] In other words, we decrease the distance between two points until we cannot resolve them separately anymore. Resolution is the ability to tell points/objects apart, to resolve them.

Many elements play a role in the resolution of a system. We will separate these differences in two, the resolution of the sensor and the resolution of the lens system will be explored later in this section.

It is common knowledge that the pixel size and quantity define the resolution of a sensor.

Megapixels is a measurement of how many millions of pixels a sensor has. The sensor sizes are standard but not all sensor sizes have the same number of pixels. A large number of megapixels increases the resolution.

High quality surveillance systems have 4K sensors (four times as many pixels as a 1080p sensor). Cameras on a budget will oscillate between 1080p and 2K. 1080p sensors have a resolution of 1920x1080 pixels. 2K sensors have a resolution of resolution of 2560x1440 pixels, and 4K sensors have a resolution of 3840x2160 pixels. [23] [24]

But when exploring resolution there is much more to it. The highest frequency a sensor can resolve is called the Nyquist frequency. It can be defined as two pixels or one line pair (2 pixels=1 cycle=1 line pair, or lp).

In the industry, a common way to approach the sensor resolution (ξSensor), also referred to as the system's image space resolution (ξImage Space), is "by multiplying the pixel size (s), in microns, by 2 (to create a pair), and dividing that into 1000 to convert to mm." [25]

$$\xi\text{Sensor} = \xi\text{Image Space} = \left(\frac{1\ lp}{2 \times s}\right)\times\left(\frac{1000\mu\text{m}}{1\ mm}\right)$$

We can also determine the minimum resolvable spot in a scene by taking the ratio between the sensor size (horizontal, vertical, or diagonal) and field of view (FOV). This relationship is also called system magnification. [25]

$$m = \frac{H}{FOV}$$

By determining the imaging space resolution and the system magnification we can make the lens choice more convenient.

Choosing between the sensor resolution is also a matter of bandwidth. Higher resolution means more data transfer, and it requires faster speed.

Another detail to consider is the frame rate the sensor enables. The rate of frames per second (FPS) indicates how many images are taken in one second. More frames per second results in a smoother and higher quality video. Usually, the frame rate found in security cameras varies from 30 to 60 FPS, where the high end of this range is used for traffic monitoring. [26]

The tradeoff between a higher number of frames per second is that it also increases the bandwidth and storage requirements. Since the goal with this surveillance system is not to track fast moving objects but people inside a room, a 60 FPS is not necessary.

Chapter 4 – Related Standards and Design Constraints

4.2 Practical Constraints

4.2.1 Time

For this project, the primary constraint is time. Since this is a senior design project, we have very strict regulations and deadlines that must be met. This only gives our group a limited amount of time to conceptualize, research, design, and fabricate our system and idea. Due to this restraint, we have had to come up we different solutions and follow different paths to focus on meeting our deadlines rather than fully fleshing out a fully optimized final product.

One of the key challenges we faced is that we only had a single academic calendar year to construct and demonstrate a functional system. We are given no extensions and have firm deadlines that must be met to successfully complete the course and pass. Fortunately, we were able to gain a bit of a head start as half of our group was formed in the previous summer semester and started workshopping the idea that we wanted to do. This allowed us to mitigate some pressure as we progressed because we had the general idea, and we can jump straight into research and development immediately.

On top of designing the system, we also would have to have ample time set aside to conduct extensive testing and debugging, all within the timeframe we were given. In any sort of design project, we assume that we will run into setbacks and errors, so we must allocate a sufficient timeframe that can encapsulate this threat if need be. Unforeseen issues that weren't accounted for are a hindrance to the success of the project plan and the passing of the course.

Another related issue would be the delay that we could see when ordering the parts for the project, as a numerous number of variables can affect whether the components, we ordered arrive in time to complete the project. Projects like this, with such a limited time span, often face delays at this stage because there could be potential supply shortages or issues with shipping that could deter the design's completion. Without the components for the project, we cannot move forward with the critical portion of constructing, testing, and debugging the system, eating up valuable time.

Having such strict time constraints might make us want to take shortcuts to achieve our final goal. However, having that mindset will only lead to a rushed and sloppy project that compromises the quality of the overall function. Adjustments are bound to be made to help solve issues but if those adjustments aren't drastic at such a late time, we can avoid jeopardizing the structure of the project.

Our team has a strong value that we must hold everyone accountable and withhold our responsibilities that we are given or take on. We follow the principle that was explained to us in our class where we will "Do What You Say You Will Do" or DWYSYWD. Having a set goal and working towards that goal consistently and efficiently will lead to a better product. Communication and proper planning help mitigate these potential issues that could pop up and allow us to complete our project on time and to a quality standard.

4.2.2 Economic

One of the main constraints that must be taken note of was the economic constraint. Our project has no sponsors, so the whole cost will be coming out of pocket. Due to this, we must take extra care in constructing a budget so that we have enough funds to cover the entirety of the project or not spend more than we need to. We had to carefully investigate different components and comparisons so that we can find the products that have the capability to do what we want to accomplish.

We hope to keep the entire cost below $700 while still having extra funds if something breaks or burns out during testing. By having a cost buffer of funds, we can ensure that in an unfortunate event, we allow ourselves to have less worries when working with such delicate components. Although we can replace anything that breaks, we'd like to avoid that possibility since it will only rack up a higher cost in the long run of the project.

Our research in part selection is essential when carrying out the project, as we don't want to spend an absurd amount of money on a component that has no overall functionality for the purpose of the project. Therefore, we must consider the price of components and the functionality in our research, making sure that we can use the component, or it would be a waste of time and money, both of which are very limited as Senior Design students.

The economic constraints that we place upon ourselves can be a detriment to the success of the project because of the need to buy the best products on the market that can do what we would like to achieve while also not being absurdly expensive. This requires us to do exceptional research so that we can compare different products and make sure that the functionality to cost ratio is sufficient. We can also avoid going over the budget if we give ourselves a cost buffer. This cost buffer, as explained previously, will give the team a safety net when we're in the delicate fabrication process. If something were to break, we would already have a time issue since we would need to wait for a component to come in, but instead of being over budget and over time, we can allow some leeway in terms of cost.

As long as we keep researching and making sufficient comparisons, we can choose the best products that can handle the scope of the project while also maintaining our budget and keeping that safety buffer intact.

Chapter 10 – Administrative Content

10.1 Budget and Bill of Materials

The iSPY project is to be entirely self-funded by its group members. Sponsors capable of supplying critical higher-cost items and components, like lenses, processing units, or electrical hardware, are currently being analyzed. It's the Authors goal to minimize costs and limit expenditures to less than $1000.

The table below highlights the distribution of costs across the different major sub-systems and potential components that make up iSPY. Historically, optical and photonic components are priced higher than the electronics components; allocating a larger sum of the budget for this is acceptable.

Table 10.1. *Itemized bill of materials.*

Sub-System	Components	Budget	Unit Cost	Quantity	Total Cost
Imaging Acquisition	Camera Module	$ 200.00	$ 75.59	1	$ 75.59
	Imaging Lenses		$ 43.91	4	$ 175.64
Transmission/ Receiver System	Near-IR Photodiode	$ 300.00	$ 58.91	1	$ 58.91
	Near-IR Laser Diode		$ 54.16	1	$ 54.16
	Tx/Rx Lenses		$ 43.91	3	$ 131.73
	Miscellaneous Optical Components		$ 50.00	1	$ 50.00
Computer Hardware	Microcontroller Unit	$ 50.00	$ 10.00	2	$ 20.00
Electrical Housing and Power Systems	Transmission PCB	$ 50.00	$ 20.00	1	$ 20.00
	Receiver PCB		$ 20.00	1	$ 20.00
	Power Supply Unit		$ 12.42	2	$ 24.84
	Miscellaneous Electrical Components		$ 20.00	1	$ 20.00

Display	Monitor	$ 25.00	$ 25.00	1	$ 25.00

10.2 Distribution Worktable

The distribution worktable below details the primary and secondary members assigned to each responsibility. Each group member is assigned as the primary member for a specific sub-system that makes up the overall system. However, it's important to note each sub-system strongly depends on the adjacent sub-systems of another member, making secondary member assignments equally important. Each group member will also be assigned as secondary member for two or more responsibilities across sub-systems to meet this need, encouraging collaboration and discussion members.

Table 10.2 *Distribution worktable.*

Sub-System	Responsibilities	Primary Member	Secondary Member
FSO	FSO Lens Design and Implementation	Alejandro	Gabryella
	Laser and Detector Selection and Implementation		Gabryella
	Optoelectronics integrations with PCB Housing		Robert
Imaging	Design And Align Lenses for Image Acquisition System	Gabryella	Alejandro
	Selection of Appropriate Image Sensor		Alejandro
	Optimization of Image Quality		Luke
	Integration of Image Acquisition System		Luke
Object Detection	Computer-Vision Software Design and Implementation	Luke	Robert
	Appropriate MCU Selection		Armani
	Machine Learning Algorithm Development		Robert
Signal Processing	Signal Modulation/Demodulation	Robert	Armani
	Output Video Processing and Display		Luke
	Compression Software Design and Implementation		Luke
Electrical Hardware	PCB Design	Armani	Luke
	PSU Design and Implementation		Robert
	Interface Design for Data Transmission		Robert
	Signal Conditioning and Processing		Robert

Website Management	Organize and update group's website with assignments before deadline	Luke	Robert

10.4 Milestones

The success of the project depends on individual and collective achievements. To create a good dynamic amongst group members and to maintain pace, the collective milestones encountered in Senior Design 1 and Senior Design 2 are highlighted below.

Table 10.3. *Senior Design 1 Milestones - Project design phase.*

Senior Design I Milestones		
Task	**Status**	**Deadline**
First group meeting	Completed	August 15, 2024
Project selection/Brainstorming	Completed	August 25, 2024
Group meeting to discuss D&C document and committee formation	Completed	August 27, 2024
Idea presentation to Dr. Kar	Completed	August 29, 2024
Submit Divide and Conquer 10 pages report	Completed	September 6,2024
Committee Formation	In progress	September 6, 2024
Divide and Conquer Meeting with Advisors	Completed	September 9, 2024
Fix Divide and Conquer report	Standby	September 27, 2024
Upload Divide and Conquer Report on website	Standby	September 27, 2024
Midterm Demo (CREOL)	Standby	October 8, 2024
Upload 75 Page Report	In progress	October 25, 2024
75 Pages Report Meeting with Advisors	Standby	October 28-30, 2024
Fix 75 Pages Report	Standby	November 8, 2024
Upload 75 Pages report on website	Standby	November 8, 2024
Final Demo (CREOL)	Standby	November 21, 2024
SD1 Final Report	In progress	November 26, 2024
Upload Mini Demo Video on website	Standby	November 26, 2024
Project Research	In progress	-
Order Parts	Standby	Before Winter Break

Table 10.4. *Senior Design 2 Milestones - Project creation phase.*

Senior Design II Milestones

Task	Status	Deadline
Project Research	In progress	-
Prototype Development	Standby	TBD
Testing	Standby	TBD
Troubleshooting	Standby	TBD
Optimizing	Standby	TBD
CREOL Showcase	Standby	April 25, 2025

Declaration: We hereby declare that we have not copied more than 7 pages from the Large Language Model (LLM). We have utilized LLM for drafting, outlining, comparing, summarizing, and proofreading purposes.

Appendix A – References

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Appendix B – Copyright Permission

Most of the figures and tables in this document were made by the authors themselves. Permission was requested to use Figure 2.X

Gabryella Baldaci

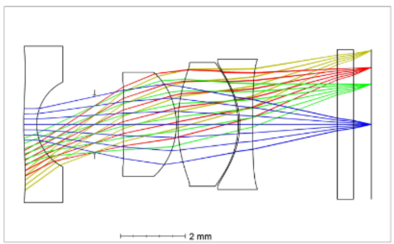
To: dongmok@gist.ac.kr; hyuksang@gist.ac.kr

Thu 9/19/2024 10:07 AM

Good morning,

My name is Gabryella Baldaci and I am a student at University of Central Florida.

I am working on a project, and as I was researching lens designs for wide fields of view and that is when I came across your paper "**Wide Field-of-View, High-Resolution Endoscopic Lens Design with Low F-Number for Disposable Endoscopy**" on this website https://www.mdpi.com/2304-6732/8/4/89
To demonstrate the idea, I would like to use your Zemax image so I am writing this email to ask your permission to do so.
My project is for a surveillance camera. My final design will be different, I have no intention to copy anything from your work. I am only using it as a reference along with other papers and patents. I would like to use the Zemax screenshot as a demonstration. This is what I have for the legend of the figure, "Figure 2 shows the design of a wide-lens system [11 - your paper]. Wide-lens and fisheye lens systems usually follow a similar structure, and this is what we currently have in mind. Our system will follow industry's frameworks and expand to match the requirements of our design."



Please let me know if you can grant me the permission.
Thank you.

Sincerely,
Gabryella Baldaci