IOWA STATE UNIVERSITY

Characterizing Infrared Sensor for Hypervelocity Asteroid Intercept Vehicle

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Project Plan Version 2

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This report entails the ideas, early design, and plan for an infrared telescope to be used for space application on the Hypervelocity Asteroid Intercept Vehicle. The following includes design aspects such as early design, lab scalability, and operating environment of the apparatus.

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Introduction

Imagine an asteroid moving towards the Earth's direction and potentially destroying it. What can we, the human race, do? Our client has come up with a concept called Hypervelocity Asteroid Intercept Vehicle (HAIV) that uses both optical and infrared sensing devices to aim their nuclear warheads at the incoming asteroid. One of the goals of this project is to assemble a prototype optical and infrared sensor package that can be implemented later on a larger scale. Along the way, we have the goal of assessing technical issues (thermal noise, cooling) following the system prototype.

Problem Statement

Our client and his team have been able to generate infrared and visible spectrum images of an asteroid and were able to simulate what images would look like if the asteroid was a great distance away. The parameters for their simulations are all theoretical and they desire to have more real-world parameters. They have also generated comparison images between the visible spectrum and the infrared spectrum. The problem is that they do not have any proof of how their simulated images or theoretical parameters compare to real values; we intend to provide this proof of concept and keep it very well documented so that our work can become of later use to them.

The feasibility of such a detection system was unknown to the client as there are many different infrared technologies available today that cover various ranges of the infrared spectrum as well as covering various ranges of operating temperature. The employment of these infrared optical lenses and mirrors was also unknown to the client. The distance of detection can be thought of as a distance between the sensor and the asteroid in space. This parameter was also an unknown quantity and clarification was sought by the client.

Concept Sketch

Our team is employed to research the various topics of infrared sensor types and infrared telescope types and to come up with answers for our client. In order to keep this from being solely a research based project with no design aspect, we also plan to deliver a telescope design. This will satisfy the class as well as the client.

On another note, as budget is an issue for us in this design, we are not going to build a final product for implementation as parts for this type of design are quite expensive. A cheap, base model, low resolution, infrared camera alone is $3500 dollars, where we were only allotted $1000. We were lucky as to have access to one of these cameras to perform lab experiments with.

As we are most likely not able to physically build anything for our final product, cost analysis will be a major component of our final deliverable. We plan to design an optical system to work with multiple sensor types then perform a cost estimate so that our client can further see the feasibility of implementation of this sort of system. It will be easiest to perform this analysis on the actual components of the telescope as infrared lenses and mirrors are commercially available. The rest of the components of this system, however, make it very difficult to find any sort of cost information. These difficult system components are things such as the infrared sensors themselves and the cryogenic cooling modules as well. Much information can be found on the actual technologies available, but very little cost information is offered.

Experiment Setup

Background

We plan to initially explore the aspects of a Galilean telescope design as a first learning experience as we dive into optics. This will include simulations of this design by using Code V software. We can tell already that this will most likely not be the final design of our system as this telescope design requires a focal length of around 4 meters, resulting in a very massive telescope. Once we have done some designing with this, and begin to feel comfortable and confident with this design, we will then look into other optical telescope designs to look for ways to increase viewing distance while decreasing apparatus size.

Scalablility

As for our experiment setup, scalability will be a major factor to keep in mind while designing our telescope. The initial detection distance that the client offered was to be able to turn the detector on from an hour out from impact. The net speed between the target and the sensor is 10 kilometers per second. This resulted in a distance of 36,000 kilometers when the device is to be turned on! To put this number into perspective, this number is equivalent to the distance of 3 Earth diameters. As you can see, it is impossible to actually test the real distance here on Earth, so we must scale down to the lab.

We plan to get our scalability factor by Planck's Law of Blackbody Radiation. The following is a short derivation, and we will begin with the formula for Radiance.

$$L = \int_{\lambda_1}^{\lambda_2} \in \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{k_B T \lambda}} - 1} d\lambda$$

where,

L = Radiance
λ = Wavelength
h = Planck's Constant
c = Speed of Light
k_B = Boltzmann Constant
$\in$ = emissivity
T = Temperature of the object

As you can see from this equation, the equation above has many constants, but is mostly dependent on the temperature of the object and the material constant emissivity. The integration can be performed for a specific temperature and material over a specified frequency band and we will get a number. Next we have the Irradiance

$$E = L\Omega$$

Where Ω is the solid angle. The solid angle can be thought of as the angle of approach, and for our application, we are going to assume that the solid angle be zero as there is a great distance separating the sensor and target. Here we assume that we are looking straight at the object. The equation for the solid angle becomes as follows:

$$\Omega = \pi \frac{r^2}{d^2}$$

Where r is the radius of the object (assumed circular) and d is the distance between the sensor and the target. Substituting this back into our irradiance equation, we get:

$$E = L\pi \frac{r^2}{d^2}$$

As you can see, the irradiance now become solely dependent on the geometry of the problem since L at this point is a constant based on the temperature and material of the object. Now we can set the irradiance value of the lab equal to the irradiance value of the real situation.

$$E_{Lab} = E_{Real}$$

After more substitution, we get:

$$L\pi \frac{{r_{Lab}}^2}{{d_{Lab}}^2} = L\pi \frac{{r_{Real}}^2}{{d_{Real}}^2}$$

Then after some boiling down, we get to our final scaling factor that shows a nice linear proportion:

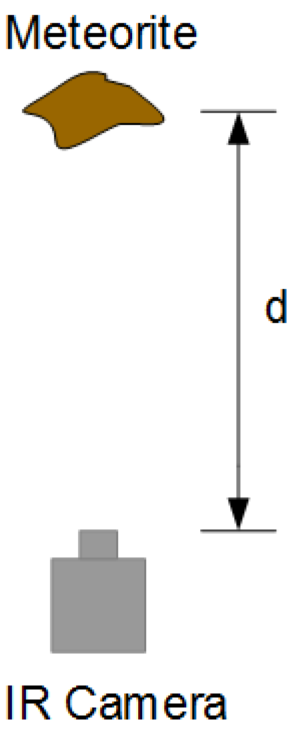
$$\frac{r_{Lab}}{d_{Lab}} = \frac{r_{Real}}{d_{Real}}$$

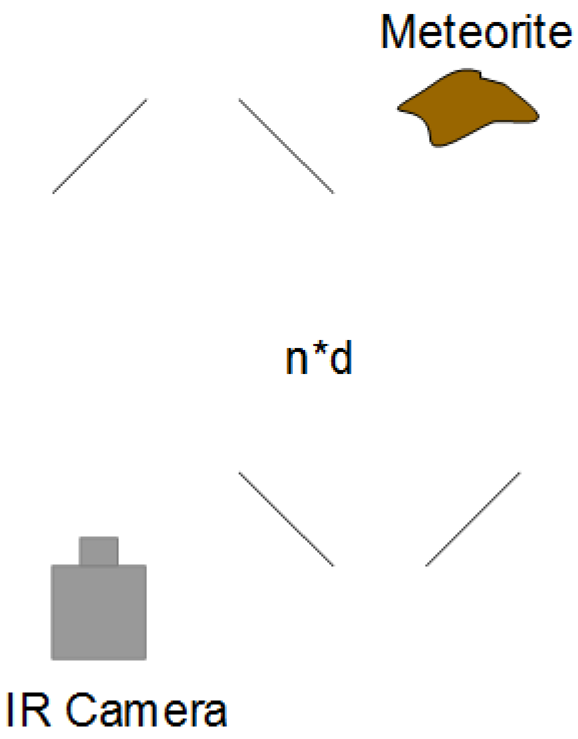
We can now relate our experiment setup to a real world application in space.

Lab Setup

Our lab setup entails heating a meteorite sample to just above room temperature as the nominal temperature range of an asteroid in space is between 180 and 300 Kelvin. Our camera is sensitive enough to detect the object and have high contrast to the similarly heated background. This helps to prove that there is a very good signal to noise ratio.

We have a camera setup a specific distance from the object. We try to get the solid angle as close to zero as we can to keep our scalability factor holding true. In our early experiment setups, we used only the default optics that came stock with the camera. As we begin to develop our telescope design, we hope to eventually employ the use of a few infrared lenses or mirrors to increase the viewing distance within the same room. Below, the image on the left depicts our initial experiment setup. The image on the right depicts our later experiment setups. **THE IMAGES ARE NOT TO SCALE.**

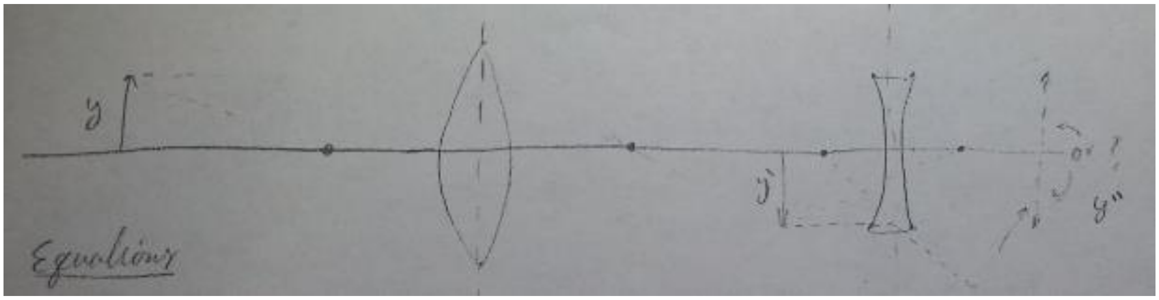




System Block Diagram

For our system, there is not much of a block diagram as the design is mostly optical design rather than electrical. There were many block diagrams in our old design of the turntable that we were initially designing, but that is all trash now and irrelevant.

As stated earlier, the initial telescope will be based on a Galilean telescope. The Galilean telescope employs a convex and concave lens in order to magnify an image. below is a diagram of a basic Galilean telescope.



Some pitfalls with a Galilean telescope are that there is a low field of view. This means that the larger an object is, the harder it will be able to fit onto one image at smaller distances.

Another pitfall to any telescope design is the fact of lowered brightness. This is due to the fact that the largest amount of light any passive apparatus can see is what is given. This means that the telescope takes one source of light, and spreads it over a larger area. This takes a toll on brightness. Telescope imagers get around this by increasing the exposure time. This may not be a feasible option for this application as we are traveling at high rates of speed.

System Description

As we approach the object, we may have to focus the image onto a CCD to keep a crisp image for the tracking system. We do not want to have too much noise in our system due to lack of focusing. Our initial telescope exploration is very static and does not focus, thus, we may need to look into designing for large focal range.

Operating Environment

The operating environment is very harsh for electronic devices. We all know that outer space is a vacuum, the lack of pressure may be the least of our worries when designing this apparatus. With space comes cold. According to our client's team, the background temperature will be around 3 to 6 Kelvin. This will help as it will create a huge difference between object temperature and background temperature. This will increase our margin for signal to noise ratio, but it may affect the workings of our electronic devices as semiconductors are very temperature dependent.

Not only may the electrical devices become too cold, they may also become too hot. Since space is a vacuum, it lacks the ability to dissipate heat. This means that although we may have heat sinks on our devices, the heat has nowhere to go and will remain in one spot. So, we need to have safeguards for extreme cold as well as extreme heat.

Functional Requirements

The first most important requirement of our design is to be able to detect an object from a great distance while maintaining quickness of gathering the images with the least amount of blur and noise.

The second most important requirement will be to be able to focus over a great range of distances as well. When we are far away from the object, we need not to focus very much, but as we get closer, the image size increases more rapidly. Therefore we must begin to adjust the image more frequently and more rapidly. There is no room for low-pass filtering effects from our apparatus in a hypervelocity application.

Non-Functional Requirements

An example of a non-functional requirement of our system may be the design of the housing of our apparatus.

Market Literature and Survey

- Optical and Infrared Sensor Fusion for Hypervelocity Asteroid Intercept Guidance by Joshua Lyzhoft, Dalton Groath, and Bong Wie
    - In this paper, the team investigated the technical feasibility of a new guidance system which combines optical cameras and infrared sensors.
    - Before this, optical cameras were used for their cost-effectiveness but could only detect the side of the asteroid facing the sun due to the light reflection.
    - Having an infrared sensor, it would provide high speed image capture of the whole asteroid and with the data obtained, it will combine with the optical data to create a defined target for the guidance system to hit and have the asteroid disintegrate.
- Design and Characterization of Adaptive Microbolometers by Woo-Bin Song and Joseph J. Talghader
    - We researched mostly on finding a specific infrared sensor type that would fit our wavelength requirement and a microbolometer was the most suitable choice.
    - The wavelength characteristics of an asteroid ranges from 8.5um to 15.5um whereas the range of detection of the microbolometer is approximately from 6um to 20um.
    - The great characteristic about the microbolometer is that it does not require a powerful cooling system to have it run optimally.
    - But our project requires a precise reading, we have considered putting a small cooling system on the sensor device to cross out any discrepancies in our readings.

Deliverables

The deliverables have changed since the first version of our project plan. Instead of developing a system to heat an object to a specific temperature, we have turned to designing a useful infrared optics system.

The design of our infrared optics system will be our primary deliverable by the end of the Fall semester. We hope to be able to have some infrared mirrors and lenses setup for our lab experiments to prove that it works so that we will have a working demo to show people.

Our second deliverable is less of a priority, but none the less required for our application as we are not actually implementing anything. This second deliverable is the cost analysis of implementation of our system. This way we can design an expensive working system without exceeding the small budget that we were allotted.

Work Plan

We were able to maintain a great pace with our initial work plan of the turn table design, but as that is now irrelevant we must come up with a new one. Our current plan is to take advantage of the extra time we have during the summer to learn more about optics and verify our current exploration of the Galilean telescope design. We then will move into the semester ready to get going on newer and more modular telescope designs. We will also be ready to perform more lab experiments on characterizing our microbolometer infrared sensor.