1.0 IDENTIFICATION AND SIGNIFICANCE OF THE PROBLEM OR OPPORTUNITY

PanX Imaging Inc successfully completed a closely related SBIR project for the AFRL in 2004 (AF04-227, Small Aircraft Self Protection, TPOC Dr. Duane Warner). The project objective was to propose a sensor capable of identifying and tracking a threat to a UAV. The algorithms we developed, focused on the detection of a missile and tracking it in real time. The effort was accomplished in partnership with General Dynamics (GDAIS), also in Dayton. The AF06-220 Passive Three-Dimensional Imaging and Ranging SBIR is a natural follow-on to the results reported in AF04-227, in tandem with the commercial photographic technology developed by PanX. Our innovations, teamed with General Dynamics' extensive expertise in combat identification, automatic target recognition algorithms, and track record of bringing sophisticated products to market will ensure that Phase I development can seamlessly progress to the Phase II level and beyond.

The Phase I effort solves the problem of mathematically extracting 3-D imagery and ranging data from an optical sensor. But in a larger context, it defines an innovative, new optical sensor that serves as the platform from which to extract this data. This overcomes many present limitations of UAV optical sensors without increasing cost. This is accomplished by harnessing existing electro-

Figure 1. Our conceptual Wide Field of View, 3-D sensor provides a cost effective sensing solution for real time surveillance, tracking, and ranging on mini-UAVs.

optic technology available in commercial-off-the-shelf (COTS) components. Since video images are the data source, they will also be available for remote viewing. The highlights of our technology are summarized in Table 1.

Highlights of the PanX Imaging Sensor Technology

Features & Characteristics	**Benefits**
No Gimbals	Reliable & Mechanically Simple
	Economical
	Remove & Replace Unit
Compact & Robust	Simplified Handling/Installation/Maintenance
	Small & Lightweight
3D Imaging Geometry & Frame of Reference	Simplified Algorithm Demands
	Intrinsic 3D Mensuration Capability
Object Recognition & Tracking	Fast Image ID Processing Algorithms
	Fast Image Difference Algorithms
	Simple Angular Difference Integration
Multi-Lens Array	Wide Field of View (WFOV) + High Resolution
	No Optical Switching from Hi-Res to WFOV
High Resolution Sensor	Improved Image Quality
Multiplexed Imaging	A Single High Performance Sensor
	Multiple Lenses at Video Frame Rates
	Cost effective
	Commercial Components
	Simultaneous Video for Data & Viewing

Table 1. ***PanX Imaging and General Dynamics provide an innovative edge***

1.1 PROBLEM DEFINITION & SOLUTION

In theory and practice, images of moving objects from visible and IR camera systems provide data that must processed to determine range and speed information. A conventional camera images the light from a single lens onto a single two dimensional sensor surface. The algorithms used to extract range and speed information from such a flat, two-dimensional image are quite limited, and prone to errors in probability of detection ($P_{d)}$ and high false alarms ($P_{f\ a}$). Stereo imaging provides more accurate range and speed information because it introduces a triangulation component from which to collect data. Incorporating a stereo imaging system into a MTS sensor balls currently used on UAVs is problematic. The calculations applied to single sensor data are further complicated by UAV motion relative to the motion of the object. Although image stabilization schemes and GPS data help mitigates this problem, the mechanical and computational burden of single lens imaging and ranging are non-trivial. PanX Imaging, in cooperation with General Dynamics, proposes a novel approach: the Multiple Lens Optical Sensor (MLOS). It solves these problems and improves surveillance sensor performance while providing simultaneous WFOV and Hi-Resolution. Additionally, the MLOS package is smaller, lighter, very rugged and less expensive.

2.0 PHASE I TECHNICAL OBJECTIVES

2.1 PROJECT GOALS

1. Propose a sequence of algorithms that image, detect and track an object in a 3-D frame of reference; exploit the concept of Optical Flow (OF); leverage GPS data; correlate object of interest pattern recognition data; and calculate linear and angular data to provide range, heading, and speed information. The algorithm investigation seeks to achieve high P_d and low $P_{f\ a.}$

2. Construct and/or purchase hardware needed to record video clips and process the image data required. Investigate critical issues leading to the development of an MLOS sensor package suitable for a mini-UAV platform.

3. Outline a Phase II program to develop and construct a prototype sensor that can be mounted in a mini-UAV platform. It provides the basis to test and refine the algorithms: Determine data processing, image and data transmission parameters: Evaluate the optical system and algorithm performance within an extensive set of operational scenarios. The Phase II investigation will open a development path for a MLOS sensor package configured to conform to the fuselage of mini and micro-UAVs. Such a package significantly enhances both surveillance and flight path navigation in a tactical theater of operation.

2.2 PROJECT OBJECTIVES

The knowledge gained from AF04-227, Small Aircraft Self-Protection, provides a logical starting point for investigating passive 3-D imaging and ranging. We will:

1. Leverage the algorithm sequence used to identify and track a SAM launch.
2. Use data from our experiments to determine resolution limits and characterize the trades involved in developing a Phase II prototype.
3. Employ some of the equipment and software previously purchased.
4. Investigate several of the optical multiplexing concepts resulting from the 2004 project.

The image integration algorithms utilized by PanX for multi-lens still photography provide a solid underpinning for 3-D sensor mensuration and ranging. PanX has successfully produced a variety of WFOV photographic images within a cylindrical frame of reference with a multi-lens/multi-sensor camera. The PanX knowledge base in WFOV imaging that directly applies to this project are:

5. Algorithms to determine variance from optical centroids in a 2-D cylindrical frame of reference, which will cleanly migrate into a 3-D frame of reference.
6. Algorithms used to integrate or “stitch” multiple images into a single WFOV image that offer proven methods to detect and align common elements in adjacent images.

General Dynamics has considerable experience developing successful target detection and tracking algorithms. They possess a considerable library of image characterized real world objects that can be utilized for testing a prototype sensor. Successful completion of Phase I will define the growth path to a system suitable for a multitude of military applications including UAVs, smart munitions, small aircraft defensive system suites, surveillance systems and land vehicle self-protection. General Dynamics brings a 50-year history of working closely with AFRL. Together, we will work closely with the Government to establish performance criteria that are acceptable to all members and ensure that system goals are met.

Table 2 summarizes the Goals of the Phase I project. They harness the MLOS technology to the task of AF06-220 “Passive 3-D Imaging and Ranging,” *and* simultaneously broader possibilities. At the end of Phase I, this effort will answer the main question: Can a MLOS system satisfy the requirements of military and commercial users for 3-D imaging and ranging? It also investigates how surveillance, object ID, object tracking, collision avoidance, and self-protection can realize significant improvements in performance. The goals and objectives were chosen to both propose a system to image & range an object of interest, *and* to move the benefits of MLOS sensing from concept to reality. The overview is summarized in Table 3.

Phase 1 Goals Summary	
1. Develop a set of algorithms capable of…	Identifying & tracking objects in a multi-lens 3-D frame of reference
	Exploiting the advantages of Optical Flow
	Extracting range and speed vectors from multi-lens imaging
	Integrating GPS data
	Correlating image/object library data
	Achieving a high P_d and low $P_{f\,a.}$
2. Construct an optical test bed capable of…	Imaging a moving object in a multi-lens 3-D frame of reference
	Simulate multiplexing the lens array onto a single 2-D sensor
	Downloading the video clips to a personal computer for processing
3. Outline a Phase II program	Develop optical & packaging characteristics and specifications for a multi-lens prototype sensor
	Investigate and specify the key components for a multi-lens prototype sensor
	Develop an algorithm flow diagram
	Estimate the processing requirements and required hardware
	Develop a processing hardware flow diagram
	Explore multi-lens sensor potentials in mini & micro UAVs
	Explore the performance envelopes in both VNIR & LWIR

Table 2.

Multi-lens Sensor Development Forecast	Today	Phase I	Phase II
WFOV+Hi-Resolution Photography	√		
WFOV+Hi-Resolution Video		√	√
Object ID & Tracking		√	√
Object mensuration (range, bearing, speed, instantaneous position)		√	√
Image/Object correlation		√	√
Surveillance, Self-protection, Collision Avoidance/Navigation		√	√
High Probability of Detection		√	√
Low False Alarm Rate			√
Night/All Weather Capability			√

Table 3. Possessing the Know-How

2.3 TECHNICAL DISCUSSION

2.31 SENSORS IMITATE NATURE

Nature provides two fundamentally different vision models, the compound eye common to insects, and the camera eye common to mammals. The sensors used in surveillance generally depend on the camera eye model. It has the advantage of a WFOV at low resolution and, with magnification optics, can easily switch to a narrow field of view and provide a high quality image. Pixel count is important to a camera eye. More pixels usually means higher performance. The human eye, for example, has 6 million cones and 125 million rods in each eye at refresh rate of around 30 Hz and has the foveal or acute zone of high resolution. The quality and flexibility of the imaging optics is important to high performance in a camera eye.

The compound eye is designed for high performance in different ways. Each insect, arachnid, crustacean, etc. employs a compound eye that is specifically designed to enable them to survive within their ecological niche. Compound eyes in the natural world trade the long range and rich detail of a high resolution image for a short range WFOV and a keen ability to detect motion. The low resolution trade is helped in part, by a relatively high sampling rate. High sampling or flicker rates are combined with fast image processing in the brain. The fly eye has approximately 50,000 pixels that refresh at a rate of 300Hz. This combination results in highly effective position and movement detection. It takes the acceleration of fly swatter to beat that 300Hz refresh rate. In the natural world, flying insect compound eyes exploit "optical flow" (OF) to detect objects and determine flight path. In a sense, insect brains are hard wired. If the impulses from the eye are perceived as recognizable patterns, the insect responds with predictable behavior. This optical correlation ability reduces the processing load and speeds response time.

The PanX MLOS concept merges key features of both vision models. The MLOS exploits multiple lenses, optical flow, high sampling rate, and optical correlation—without sacrificing high resolution or high refresh rates.

2.32 MULTIPLE LENSES CONNECT WITH GEOMETRY

An important advantage of PanX MLOS technology is our method of exploiting the geometry of a 3D lens/sensor array to simultaneously achieve WFOV and high resolution. Positioning lens/sensor pairs on the facets of a regular platonic solid such as a double truncated icosahedron, often called a Buckyball (figure 2), establishes an exploitable frame of reference from which image data is harvested from the 3-D sensor array. This concept is a three dimensional extrapolation of the binocular vision we use to reckon relative distances and recognize objects. The 3-D Buckyball frame of reference links the

Figure 2

sensor images into a mathematically precise 4pi steradian mosaic and enables mensuration of objects within the mosaic.

2.33 EXPLOITING OPTICAL FLOW

Optical flow (OF) is a wonderfully efficient and simple way to determine position and movement. The speed and simplicity of the 16x16 pixel photosensor array and inexpensive OF microprocessor in an optical mouse is an example of how the OF process can be exploited in real time. Essentially, OF uses the “texture” in images as a source of motion cues. The recent successes in the flight control and navigation of small autonomous flying robots owe much to the OF models existing in the natural world. Vision systems that relied on intensive computation were eclipsed by much simpler and faster computation made possible by understanding and applying OF.

The missile tracking algorithms developed for the AFRL by Bob Wachtel in the AF04-227 project, completed in partnership with General Dynamics, exploit OF in image capture, image processing, image data reduction, and detection of image movement. These algorithms can be applied within the 3-D Buckyball frame of reference to extract information regarding the position of an object of interest. The OF algorithms are critical to maintaining large (>90%) Probability of Detection, P_d, and minimizing (<1%) Probability of False Alarms, $P_{f\,a}$.

2.34 OBJECT SIZE AND DISTANCE DETERMINATION

Nature’s compound eyes use relatively simple—yet clever ways to precisely calculate distance by employing a combination of techniques. Like OF, the simplicity is elegant and profitably applies to military and commercial sensing.

First, since nature’s compound eyes have poor resolution, it is difficult to gauge distances using image size alone. Some insects overcome this limitation by correlating pre-programmed image sizes to what they are seeing in the external world. Optical correlation techniques are commonly used by the military in target detection and discrimination. General Dynamics has extensive libraries that can be programmed into a sensor’s memory and put to work with MLOS technology.

Secondly, another common technique used by insects to determine absolute distance is gauging the disparity of two retinal images. This is the familiar binocular cue—even compound eyes exist in pairs. Within a certain range, a nearby object point will be imaged. The optical axes of the images will deviate by a particular angle. In insects, the usable range is limited due to the relatively short distance between the eyes and the type and position of the axial sensor bundles called ommatidia. Ranges are generally less than a meter.

Calculating both intra-lens and inter-lens variance from optical centroids, is a key feature of MLOS technology (figure 3). Extrapolation of a binocular, cylindrical frame of reference into a Buckyball, spherical frame of reference facilitates local measurement precision in a WFOV frame of reference. Because of the relatively high resolution of COTS sensors, and the precise nature of both the pixel array and MLOS lens array, we can extend the technique to much longer ranges. The useful limits remain open for trades, but should be appropriate for low altitude surveillance.

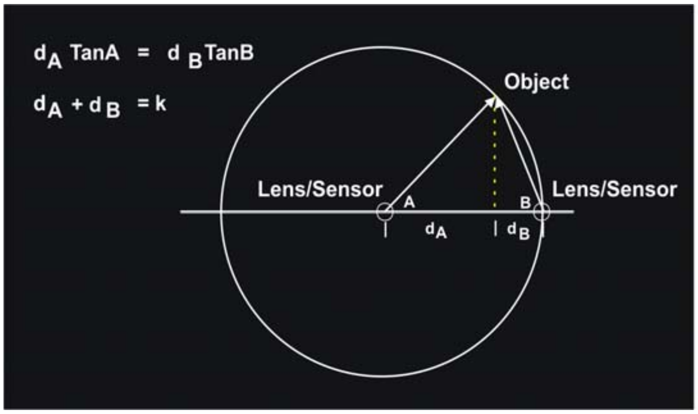


Figure 3

2.35 ACUTE ZONE ADVANTAGE

Compound eyes in some insects also have “acute zones” like the human foveal zone. Acute zones serve to detect other insects at distances greater than a meter. The praying mantis is a perfect example of acute zone advantage. The mantis has a flat area on its compound eye that is relatively high in resolution and very directional. It can also articulate its head to aim the acute zone. This predator has the ability to remain relatively motionless while scanning for prey - a lethal advantage.

The MTS Sensor Ball in a UAV such as the Predator is an excellent technological parallel to the acute zone advantage of the mantis. It is capable of both WFOV at low resolution and can switch to high magnification to view an object of interest at high resolution. However, the MTS Sensor Ball is limited by some well known trades.

WFOV images and magnified images are an either/or choice. Objects of interest can be identified at relatively low resolution in the WFOV - then the Sensor Ball switches a lens group to magnify the image while gimbals move to aim the optics at the identified object. This requires a mechanical system with the attendant complexities. MLOS technology offers an innovative optical alternative with the potential to overcome the limitations inherent to the MTS Sensor Ball. We call it “Sensor Multiplexing.”

2.36 SENSOR MULTIPLEXING

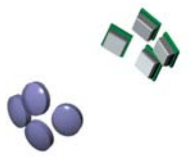


Figure 4

The original PanX Buckyball concept positioned a lens/sensor pair on selected opposing facets of the Buckyball (in figure 2). Figure 4 shows the free body lens/sensor pairs. Experimentation during the AF04-227 project proved that this approach would require an unreasonably large number of lenses feeding 6Mpixel sensors to achieve simultaneously WFOV and high resolution at a 2.5 mile range—in still photography. Our goal was to move quickly to video and keep the costs down.

Further investigation indicated that sensors capable of typical video frame rates were in the 1-3Mpixel range. Presently, these sensors have reached the 5Mpixel level and are likely to climb still higher now that high quality CMOS sensors are coming of age. However, these sensors scan at relatively slow frame rates. As of 2005, megapixel, high speed sensors capable of 500+ frames per second are readily available in the commercial market. A high speed, megapixel sensor can be exploited through a multiplexing technique that sequentially feeds the individual images from a 3-D array of lenses onto a single sensor at over 30fps/lens. In essence, the sensor can be multiplexed in the time domain if the light from each lens can be modulated by on/off light valves. Figures 5 & 6 show a hypothetical Sensor Ball array of fifteen lenses. Fifteen lenses were chosen in a pentagonal array because this is the most tightly packed subset of a Buckyball's facet groupings. The pentagonal group provides an acceptable overlap in field of view between adjacent lenses. The overlapping of images enables data continuity and exploits the Buckyball's fixed 3-D frame of reference.

The concept shown (in figures 5 & 6) is only one example of the several optical multiplexing solutions. It was chosen because it clearly and simply illustrates the fundamental concept of optical multiplexing.

Figure 5

Multiplexing images from many lenses onto a single sensor saves cost and reduces system complexity and weight. Imaged light from all fifteen individual lenses will sequentially fall onto the megapixel sensor plane. We can enhance resolution still further with magnification—using a scheme similar to the MTS sensor ball. Any image, or subset of images from the fifteen lenses can be fed into a fast response zoom lens assembly that switches from normal to high magnification (see figure 6). Multiplexing extends the benefits of high resolution to the entire WFOV lens array. Each lens or group of lenses will have sufficient resolution to determine object identification, discrimination, ranging and tracking. Light valving or modulation is the first key to multiplexing.

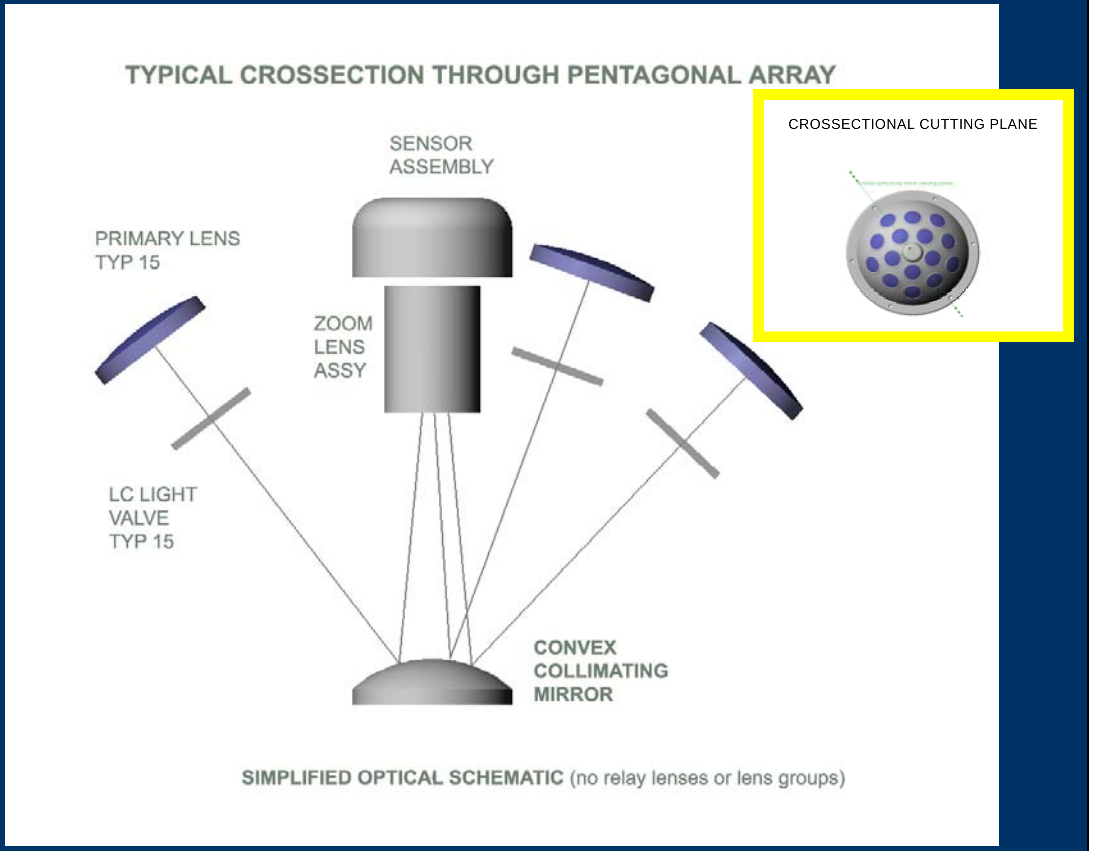


Figure 6. ***PanX Imaging's Multi-Lens Sensor Array Concept***

Software is the second key. A suite of algorithms will be used to: identify an object of interest; control the light valving by selecting the set of lenses that identify and track the object of interest; control the magnification; run size, speed, distance and heading calculations; determine if several scan cycles should temporarily return to normal magnification to check the WFOV big picture for other objects of interest; determine if the sensor can be scanned at a rate that optimizes the quantity of incoming light for high resolution processing, or optimizes the sensitivity for object movement. Algorithms capable of "stitching" a single WFOV image for remote display and viewing will also be available. This software may be located at the command center rather than in the aircraft. Control of either high resolution WFOV or magnified narrow field of view imaging can be automated or determined by human override.

Multiplexing enables the sensor to perform intelligently by electro-optically controlling the field of regard and object of interest resolution—without the mechanical demands and viewing limitations of gimbals. The extent and methods by which these potentials can be exploited requires exploration and development beyond the scope of this Phase I project, but are within the scope of a Phase II project.

Phase I will characterize two basic techniques for modulating light from multiple lenses onto a single sensor. The image light can be modulated either by either transmission or reflection. Transmission: light passing through an on/off valve such as a liquid crystal layer; or reflection: light reflecting off a valve such as a digital micro-mirror (DMM) that reflects either to the sensor or an off-axis dump. Figure 6 shows how liquid crystal (LC) light valves can handle transmissive modulation and serves to illustrate the transmissive concept. Other transmissive optical solutions include, but are not limited to prisms and off-axis parabolic mirrors. The reflective technique could employ low end commercially available digital micro-mirror arrays. Both fast LCs and DMMs are now commodity items, and in theory, can modulate light at speeds in the range needed. Investigating modulation hardware will help determine the optimum configuration for the PanX MLOS sensor in a mini-UAV platform.

Coherent fiber bundles offer a third multiplexing technique to carry low resolution images from a multi-lens array to a single sensor. Each lens will image into its bundle input end and the bundle output end will be imaged onto the sensor plane. Thus the sensor will be mapped in a fixed frame of reference with a mosaic of images. Each lens will have an assigned area on the sensor plane. Optical Flow will dominate the algorithm architecture. This multiplexing technique might work well in micro-UAV applications when combined with an Acute Zone that has sufficiently high resolution for real time video. There are a variety of trades in this fiber optic multiplexing technique. Although this multiplexing technique is beyond the scope of AF06-220, pursuing the potential suggests a high payoff SBIR investigation. Potential applications include a Humvee RPG detector that could either dispense a countermeasure or navigate the vehicle out of harm's way; and an unattended swimming pool alert sensor for detecting a possible drowning. Flight path navigation also has much potential.

Finally, multiple MLOS sensors can be integrated into the airframe of UAVs and mini-UAVs to provide up to 4 pi steradian coverage.

3.0 PHASE I WORK PLAN

SBIR Phase I Work Plan

Task	Description	Mo 1	Mo 2	Mo 3	Mo 4	Mo 5	Mo 6
1	Investigate algorithms required for object of interest identification and tracking	√					
2	Investigate Optical Flow algorithms		√				
3	Investigate the application of object and feature identification and recognition correlation algorithms and architectures		√	√			
4	Investigate object of interest mensuration for harvesting range, bearing, and speed			√			
5	Investigate the integration of GPS data				√		
6	Determine sensor optical requirements & trades	√	√	√			
7	Build & calibrate the optical test bed		√	√			
8	Gather image data using optical test bed			√			
9	Analyze & apply algorithms to image data			√	√		
10	Investigate sensor hardware requirements & trades			√	√		
11	Create trade-off matrices including P_d & P_{fa} considerations				√		
12	Optimize system algorithm architectures					√	
13	Characterize system data processing demands					√	
14	Characterize requirements for night and all weather capability					√	
15	Formulate a physical sensor design concept for mini-UAV				√	√	√
16	Discuss a physical sensor design concept for micro-UAV				√	√	√
17	Prepare Phase I Final Report						√

Table 4. ***PanX efforts will follow this logical work sequence.***

3.1 THE MLOS OPTICAL RANGING ARCHITECTURE

Much of the project work proposes to explore the potential of a multiplexed Multi-Lens Optical Sensor package because it is the heart of the "Tactically Relevant Platform" referred to in the AF06-220 title abstract. The MLOS sensor has the potential to advance UAV optical imaging to a higher level of performance. Ranging is part of it. Optical range finders that function opto-mechanically, harness the power of two optical images separated by a relatively short distance that are focused on the same object. The resulting angle and lens position allowed the range to be triangulated. Their accuracy relied on high quality optics and meticulous mechanical manufacturing and calibration. The MLOS is an electro-optic extrapolation of the same basic principle in 3-D, using modern sensors and powerful numerical processing. Multiple lenses provide a higher level of function than a single lens. This advantage increases the P_d and $P_{f\,a}$ of the object of interest position and facilitates trajectory predictions.

It's important to note that any algorithms developed to passively range an object will profit by the MLOS's 3-D frame of reference.

The architecture outlined below explains how the MLOS will tackle the problem of imaging and ranging an object of interest with the givens included in the abstract—in combination with its own inherent capabilities. The detailing of this architecture is an integral part of the work plan.

Inputs:
GPS map data uploaded for a particular mission.
GPS streaming position data from onboard receiver.
Aircraft attitude (pitch, roll, yaw) streaming data.
Fixed frame of reference within MLOS field of view (FOV).
Multi-lens optical sensor (MLOS) streaming image data from onboard sensor.

Triggers:
Object of Interest (OI) initial movement detection from MLOS.
OI differential movement detection within single lens FOV.
OI differential movement detection within multi-lens FOV.

Processing:
Integrate OI image frame of reference data (GPS coordinates & MLOS centroid differences)
Track OI image size differential.
Track OI image position differential.
Calculate OI image range & heading.
Correlate OI image identification pattern.
Calculate and/or correlate OI image trajectory pattern.

Outputs:

Transmit OI range & heading
Suggest the OI identification
Predict OI time of arrival (for self-protection measures)
Adjust flight path (to successfully complete a mission or avoid collision)
Transmit real time OI tracking video

Application:

The question of how the available inputs apply to the computational workload of optical imaging and ranging is the key to the Phase I investigation. Right angle triangulation assumes a known angle and a known distance. In the case of a moving aircraft, the altitude of the ground surface immediately below the aircraft must be provided. Therefore, input from an altimeter and/or GPS must be a given and combined with topographical information. If this data is provided, then the frame of reference available from the internal 3-D geometry of the MLOS, combined with the attitude data from the aircraft can be used to determine object of interest position differences imaged over time. The refresh rate of the GPS data will provide periodic verification—but the OI position vectors will not be critically dependent on the GPS and do not require radar.

There is another predictive mathematical strategy to be exploited. Objects of interest have known behaviors that are distinctive to their specific nature. For example, missiles approach an airborne target in trajectories that can be predicted within a degree of certainty. The degree of certainty improves if the object can be identified. This capability would be a significant advantage in achieving a high P_d and low P_{fa}. The contributions of General Dynamics will factor heavily in this strategy. Assume that a table of known trajectories is available to the processing system. Data accumulates as the time from missile launch progresses—and a pattern emerges. This pattern can be compared to the table and a reasonably accurate prediction can be made regarding the time of arrival and the instantaneous position of the missile. This strategy dramatically reduces the computational burden and has the potential for rapid response. The response can be either an evasive maneuver or the launch of a destructive expendable (DEX) self-protective countermeasure as proposed by Dr. Duane Warner.

The architecture of predictive processing employed in airborne vehicles can also apply to moving OIs at ground level, where the time domain frame of reference may not be as critical and other potential benefits of the MLOS may be realized.

3.2 Algorithm Development Overview

Using 2-D images to obtain 3-D ranging data

PanX Imaging's 2004 SBIR work demonstrated that multiple lenses in a 3-D geometrical (spherical) configuration have the capability to map 3-D space by integrating the two dimensional (sensor plane) images with straightforward transforms such as slicing:

$$df(x,y,z) = f(x,y)dz$$

What is integral to this algorithm is the virtual mapping of 3-D space. It is accomplished through the reverse transformation:

$$\int f(x,y)dz = f(x,y,z)$$

3-D space can be recreated through the integration of "slices." The work in AF04-227 demonstrated this capability through simple trigonometry. By knowing the location in space of a specific point on the MLOS sensor plane, and by knowing the geometry (in the x, y, and z axes) of the individual locations of the sensors, the 3-D space which the multiple lenses are imaging is recreated.

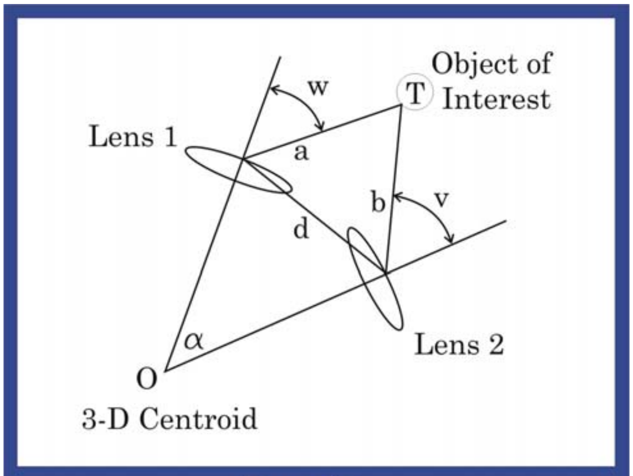


Figure 7

Thus, in Figure 7, by knowing where the point **O** is in space and by measuring the angles **w** and **v** and by knowing the locations of the rays **a** and **b** intersecting the sensors, we are able to calculate the ray from point **O** to intersection **T** (range) in this particular slice.

The two lenses in Figure 7, show a subset of the geometry existing between each lens in the MLOS array: **d** is the distance between the centroid of the lenses; α is the angle between them; the angle **w** is the angle between an object in space in reference to a line perpendicular to a specific lens; and the angle **v** is the angle to the same object (given that they overlap) as viewed by the adjacent lens/sensor. Knowing these angles, the intersection **T**, of line segments **a** and **b** from each lens/sensor is defined.

A set of linear equations for each line segment is generated using the form:

Equation 1: $y = mx + b$ where m is the slope and b is the y intercept.

Thus, for line segment **a** with the origin at lens :

Equation 2: $y_a = Cot(w)x$

And for segment **b** with the origin at lens/sensor:

Equation 3: $y_b = Cot(v)x$

However, for the calculations to follow, the real origin is at the centroid of the array, O. This, then requires the transformation of axes. For line segment a, with the origin at O:

Equation 4: $y_a = Cot(v)x + r$ where r is the radial dimension between centroid and lens.

For segment b with the origin at O, the transformation is

Equation 5: $\left(x^{'}, y^{'}\right) = (x + rCos(S), y + rSin(S))$ where S is the angle between radii to each lens

By then setting the two equations of the line segments equal to each other, the coordinates (and thus the distance using the Pythagorean theorem) of all common object points from the centroid of the array can be determined.

The implication of this kind of sensor architecture cannot be overstated. By adding lenses to the array and creating a mosaic image comprised individual images, the array does not have to be physically moved in order to track an object.

In effect, we are mathematically steering the image and tracking an object within the virtual field of view (FOV).

This implies, then, that the primary requirement of the PanX Imaging technology is an n-element 3-D lens array subtending a composite FOV where $n >= 2$. Furthermore, the greater the n, the wider the FOV. This capability is enhanced when all of the image streams in the MLOS array are processed in parallel.

Thus far in the experimental testing of the PanX commercial camera, the arrays have been planar (flat or cylindrical). Individual images in the mosaic form a set of what are referred to as "sub-images." Each sub-image is overlapped with its adjacent sub-image. This overlap defines regions of common image content that can be analyzed with algorithms designed to extract useful information.

Computation Reduction

Thus, mathematically we can leverage 2-D system equations that can represent the 3-D sliced processes. It is equally clear that processing can be significantly reduced by temporally shifting the slices into subsets and looking at finite differences. This is shown in Equations 6 and 7 below.

Equation 6: $V_{baseline}(x,y) = S_1(x,y) \cup S_2(x,y) .... S_n(x,y)$

Equation 7: $D_{n+\Delta t}(x,y) = S_{n+\Delta t}(x,y) - V_{baseline}(x,y)$ where $D_{n+\Delta t}(x,y)$ is a step

Dirac-like function based on a minimum difference threshold at time Δt. Note: These simple equations do not show the gain associated with predictive filters such as demonstrated by Kalman, etc.

Also note that the size of $D_{n+\Delta t}(x, y)$ is surrounded by an error region, $x + \Delta x, y + \Delta y$, such that any error < = 5 σ would not generate a loss of acquisition.

Concurrently, the number of $D_{n+\Delta t}(x, y)$ regions is determined by the threat. It is possible, then for the cumulative detection regions to be larger than the virtual environment itself. As is the case with organisms, this causes a processing overload which is corrected by limiting resolution to the near-field problem only (i.e. large angular displacements/unit time). Equation 7 represents the union of sets where each set is taken with an individual lens.

The union implies that there is a subset, $Q_{n+\Delta t}(x, y)$ such that for every point in the set, there is a direct mapping to the a point in $S_1(x, y)$ and the same point in $S_2(x, y)$. The Q_n set is the overlap set for $S_{n-1}(x, y)$ and $S_n(x, y)$

The virtual mosaic created in $V_{baseline}$ will, by definition of the tactical geometries, be quite dense but is also dependent on the Field of View (FOV). This parameter is defined in both the x and y directions as follows:

$FOV_x =$ angle from a line normal to the centroid of the lens to the furthest non-distorted object viewed at the periphery of the subtended image in the x-direction (horizontal).

$FOV_y =$ angle from a line normal to the centroid of the lens to the furthest non-distorted object viewed at the periphery of the subtended image in the y-direction (vertical).

The optical flow of the algorithm, then, is determined by the detection of intersection points T. This means that the multiplexed sensor must be able to identify common objects of interest detected in each individual image. Again, this is made easier through the introduction of time as a fourth dimension of the space. Relative motion to the sensor, then, becomes the computational reduction stimulus for each object.

Euclidean and quasi-Euclidean transformations can be done quite simply in the recreation of the 3-D virtual space. As in AF04-227, the application of unique filters was critical in creating the solution sets to which the math is applied. The algorithmic development will be to evaluate the trade-offs to optimize the solution set and move into Phase II implementation.

4.0 RELATED WORK

The following paragraphs highlight some of our relevant experience in the technologies critical to the success of this project.

The successful completion of AF04-227 Small Aircraft Self-Protection gives evidence that PanX in partnership with General Dynamics have developed viable concepts to realize significant improvement in the performance airborne optical sensing. The final report and a video clip is available showing the application of our detection and tracking algorithms to the firing of a surface-to-air missile. PanX has also supported NASA's Space Shuttle Program using our prototype photographic camera. The objective was to demonstrate to the NASA Imaging Group that it is possible to observe high resolution details at the stand-off distances typical of the Shuttle and External Tank during lift-off.

Bob Wachtel, the principal PanX investigator in AF04-227, has experience with real-time image processing applied to Ballistic Missile Defense (U.S. Army) and the Space Defense Initiative (SDI), specifically, the Forward Acquisition Sensor. Using astrophysics in conjunction with an IR-based camera, specific sectors of space would be scanned for moving targets and launch and impact points would be determined. This involved the interaction of sensor physics with available space-capable electronics and computer architectures.

Additionally, the PanX Imaging photographic camera system has been used extensively at college and professional sporting events in arenas and stadiums. This includes NBA basketball games, NFL football games, NCAA football games, NASCAR race events, and FIFA World Cup Women's soccer games. The experience gained in these venues have validated key objectives of the WFOV imaging technology:

- Very high pixel count (35+ Mpixel), allowing high resolution, quality enlargement capability
- Effective use of ambient light
- Images "in-focus" over entire field-of-view, providing the ability for feature/object-of-interest extraction
- Fixed geometry of the array provides accurate, quick integration of images

5.0 RELATIONSHIP WITH FUTURE RESEARCH OR R&D

The work completed during Phase I will validate the feasibility of utilizing the PanX MLOS concept to successfully image, detect, range and track objects in 3-D space. While the intent of this specific Phase I research is fundamental concept validation, the research and development work will also differentiate appropriate hardware and algorithm growth paths that will lead to realization of an improved UAV optical sensor system.

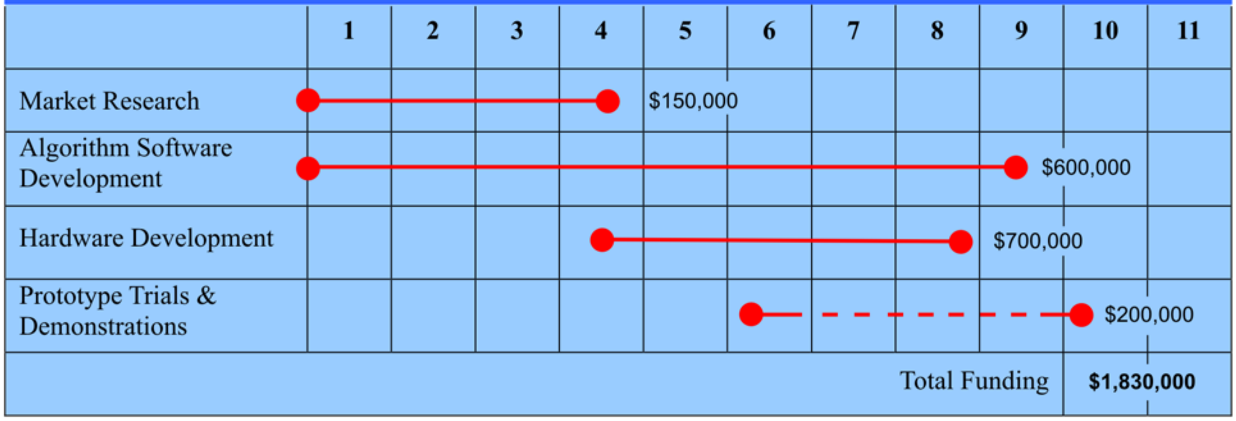
Using the knowledge from Phase I, optimized hardware packaging options for integration into a mini-UAV can be designed and constructed to test and refine the algorithms. The Phase II project will seek to develop an intrinsically rugged, simple, lightweight design that is easy to manufacture, calibrate and maintain. Work performed during Phase II will determine the feasibility of a multi-spectrum WFOV, high resolution sensor system.

Our proposal includes the investigation of both the algorithms and the sensor platform with which the algorithms will be tested in a Phase II project. The potential of this new sensor technology has attracted the interest of General Dynamics, a prime contractor with considerable resources and experience in advanced optical sensing. The scope of our proposal presents a unique set of opportunities to realize the goals of this solicitation.

6.0 COMMERCIALIZATION STRATEGY

In addition to airborne commercial & military applications, the MLOS sensor technology can be utilized in land based threat detection, collision avoidance, surveillance and security applications. To commercialize this technology, PanX Imaging is actively pursuing a partnership and capital funding for the design and development of a variety of security products targeted initially for the consumer market from SpringWorks, LLC, a Petters Group Worldwide investment company. SpringWorks, LLC specializes in the development of emerging consumer electronic technologies that can be quickly developed and marketed through the Petters Group Worldwide family of companies, which include the Polaroid and Sunbeam brands in their Petters Consumer Brands group. The market need that is being specifically addressed is in the area of COTS, do-it-yourself home security systems that will include a multi-use home video monitoring system, pool safety warning system and vehicle monitoring devices. By 2007, it is estimated that one in four homes in the United States will be equipped with a home security system. Initial plans for Petters/PanX security products, targeted at the consumer and small commercial sectors, project revenues in 2007 of approximately $24 million, growing to $135 million by 2010. The successful completion of this SBIR project, coupled with an anticipated investment of $1.8 million from SpringWorks, LLC to be utilized as shown in figure 8, will ensure that these revolutionary security products are brought to market.

Figure 8: PanX Commercial Security Market Development Prototype Timeline



PanX Imaging has evaluated potential applications for the Homeland Security and military surveillance markets including large infrastructure security (airports, government buildings, sports arenas, etc.) and perimeter surveillance, border and immigration control and sensor payloads for mini and micro-UAVs. It is the company's strategy to pursue sub-contractor opportunities with current partner, General Dynamics, to develop application specific sensor/lens technologies for these markets.

7.0 KEY PERSONNEL

Karen Blackwell will manage the Phase I work. Bill Kwolek operating as principal investigator will perform technical program management. Bob Wachtel and Don Kessler will support the technical program work. Blackwell will manage the contractual and financial aspects of this program. Data evaluation and final report preparation will be a joint effort of the team.

Karen K. Blackwell: Project Manager

Karen brings over 18 years of broad-based business experience in management consulting, project management, quality and process reengineering, sales and administrative support and associate training and development. She has diverse industry experience including computers, communications, E-commerce, document management and photographic sectors. She possesses exceptional experience in building teams and creating focus in results-orientation, thought leadership, and strategic and tactical planning to advance major and complex projects. Karen Blackwell holds a Bachelor's degree in Business Administration with a specialty in Finance from the University of Dayton and is a Certified Change Management Professional and Six Sigma Green Belt. Prior to joining PanX, Karen owned and operated a management consulting firm, and had worked in several Fortune 1000 companies holding positions of Business Consultant, Senior Director – Quality and Reengineering, Director – Process Deployment Team and Director – Finance and Administration.

William S. Kwolek: Principle Investigator

William brings a strong background in product design and manufacturing engineering with areas of specialty including the design of laser systems, optical, electro-optical and electro-mechanical scientific apparatus, rugged-duty and military computer and computer peripheral equipment and medical instrumentation. He has held positions of Mechanical Engineer, Chief Engineer, General Manager and Vice President within the ceramics, foundry, steel, laser, and scientific instrumentation industries. He has been a self-employed consultant for more than 20 years and has designed a variety of devices and systems for both military and commercial interests. From 1997-2005, he owned and operated an electro-mechanical design and manufacturing company that provided high volume deliverables to its major customer, Domino's Pizza (sensors, hand-held test instruments, and power taps). He possesses significant knowledge of mechanical systems, electronics, sensors, optics, manufacturing & fabrication, ergonomics and packaging. William holds a degree in Architecture from the University of Michigan.

Robert A. Wachtel: Algorithm Development

Robert possesses over thirty years of advanced technical design, engineering product development and deployment experience. Robert is accomplished in the areas of dial and leased line modem design, frame relay/ATM, data transport, DSP special purpose carrier modulation, photographic image compression, radio and cellular communications and network management. He has published numerous technical papers including, "All You Wanted to Know About T1 But Were Afraid to Ask", "An Introduction To Structured Software Development, A Multi-disciplined Approach", and "Automatic Speech Recognition." He holds several U.S. patents, the most notable being: "A Post-processed Modem Equalizer for Passive Determination of Line Impairments." Robert received his B.S. from the U.S. Naval Academy, a M.S. in Applied Mathematics and M.S. in Computer Science from the University of Santa Clara.

Donald J. Kessler, PhD.: Primary Consultant

Don is a General Dynamics engineer and brings to the team a very strong technical and operational background. He is a retired USAF fighter pilot with 1000+ hours flying A-10s and knows the tactical flying environment well. Prior to military retirement, he served as the Deputy Division Chief, AFRL/SNZ and continues to work closely with AFRL. His technical expertise includes electronic circuit design and fabrication and RF design, and embedded controls. He has a Bachelors degree in electrical engineering from the US Air Force Academy, and both Masters and Doctorate degrees from Wright-State University (Electrical Engineering).

8.0 FACILITIES / EQUIPMENT

PanX operates primarily from two facilities located in Manchester, Michigan and one facility in Tampa, Florida. The Michigan facilities include a 400sq ft office equipped for industrial CAD and video processing work. In addition to this office, the primary Michigan facility includes two workshops equipped for prototype fabrication and testing. The first of these workshops comprises approximately 700sq ft and is fitted with metal, plastic and wood machining equipment. The second workshop consists of 250sq ft area outfitted for electronic, electro-optical design, research and testing. Its equipment includes an optical rail with associated mounting and positioning devices, an assortment of optical, electro-optical and electronic test apparatus. Immediately adjacent to the electro-optical workshop is a 100sq ft photographic darkroom.

The secondary Michigan facility is located approximately 7 miles from the main office and contains 2400sq ft of floor space equipped for industrial manufacturing. It includes a complement of industrial manufacturing equipment including, a vertical mill, metal lathe, spot-welding and arc-welding equipment, shearing and forming equipment, heavy band saw, radial arm saw, table saw, drill press and construction staging areas. It also has an extensive inventory of hardware, materials and tooling.

The Tampa, Florida facility comprises approximately 225 square feet of design space equipped with a suite of networked computers used for image algorithm and hardware development. These computers are used for executing Matlab models and simulations as well as mechanical and electronics engineering CAD software. The equipment includes a complete electronics design, fabrication, measurement and testing facility utilized by PanX Imaging in the early design, construction, and assembly of prototype PanX cameras. This facility and equipment are frequently used as an engineering lab with various PanX subcontractors.

9.0 SUBCONTRACTORS/CONSULTANTS

PanX Imaging will utilize General Dynamics' Sensors and Intelligence Group located in Dayton, Ohio and Ypsilanti, Michigan as a subcontractor for this work. The Sensors and Intelligence Group brings significant knowledge and experience in the development of sensors and algorithms and in sensor data processing and analysis. During the Phase I project, the scope of General Dynamic's participation will be limited to providing consultation with algorithm development & optical designs and evaluation of sensor development and performance envelopes.

10.0 PRIOR SBIR AWARDS

PanX has concluded work on the following FY 2004 SBIR:	
(a) Name and Address of Federal Agency or DoD Component	Dr. Duane Warner WPAFB
(b) Date of Proposal Submission	15 January 2004
(c) Title of Proposal	Small Aircraft Self Protection
(d) Name and Title of Principal Investigator	Robert Wachtel, PanX Imaging, Inc.
(e) Title, number and date of solicitation(s)	Small Aircraft Self Protection, AF04-227, October 1, 2003
(f) Contract number	FA8650-04-M-1647
(g) Applicable topics for SBIR proposal submitted	Sensors, Electronics, Battlespace