Analysis and Selection of Components for Active SWIR/NIR Vision Systems

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***Abstract*— In this paper we elaborate on selection of hardware devices that are most convenient for use in active SWIR/NIR vision systems as source of illumination for generating image with SWIR/NIR sensors. Scenario of application in which active imaging is used in surveillance systems is explained and different implementation approaches are reviewed. Requirements for system architecture are specified and an estimate is given for expected systems performances comparing to passive solutions. Guidelines for selection of appropriate system components are given. We also propose our concept for control electronics implementation based on FPGA.**

***Index Terms*—active imaging, laser illumination, SWIR, NIR.**

I. INTRODUCTION

THE long range multi-sensor imaging systems for security and surveillance application include various imaging sensors in order to provide 24 hours visibility in all atmospheric conditions.

According to the maxima of the spectral characteristic atmospheric transmittance, there are four spectral bands selected for imaging: Visible VIS (390 nm – 770 nm), Near Infrared NIR (770 – 1000 nm), Shortwave Infrared SWIR (1 - 1.7 µm), Mid wave Infrared MWIR (3 - 5 µm) and Long wave Infrared LWIR (8 - 14 µm). VIS and SWIR images are Created using reflection of the natural or artificial light from the object and MWIR and LWIR images are created by emission of a thermal energy which is radiated from the object according to Planck radiation law. Imagers characteristic are summarized in Table I.

TABLE I
IMAGERS CHARACTERISTICS IN SELECTED SPECTRAL BANDS FOR IMAGING

Imager type	Spectral range	Imaging principle
Visible VIS	390 -7 70 nm	Reflective
Near infrared NIR	770 - 1000 nm	
Shortwave infrared SWIR	1 - 1.7µm	
Midwave infrared MWIR	3 - 5µm	Emissive
Longwave infrared LWIR	8 - 14µm	

Target detection in multi-sensor imaging systems during night relies mostly on mid wave infrared MWIR and long wave infrared LWIR cameras as they can detect thermal energy emission and don’t require additional illumination. However, in the scenario of modern security applications, it is not enough to provide only detection at long distance, but also to identify the possible threat with minimum latency, in order to make the decision and to act.

For the implementation of long range identification cameras, the most adequate characteristics have reflective NIR and SWIR imaging systems. Since their wavelength is small, pixel size can be small and resolution higher that that of MWIR and LWIR imagers. In comparison to visible range they are much less susceptible to athmospheric impairment effects.

In order to improve performance of passive SWIR/NIR imagers, active imaging, that is using laser source for illumination is needed. It is a well-known technique used for night vision or for vision enhancement in scattering environments. The elimination of the backscattering effects leads to a significant increase in the vision range.

TABLE II
COMPARISON OF REQUIREMENTS FULFILLMENT FOR REFLECTIVE AND EMISSIVE IMAGING

Imagers	Reflective NIR/SWIR		Emissive Thermal MWIR and LWIR
	Active	Passive	
Imaging in total darkness	Yes	No	Yes
Range measurement	Yes	No	No
Seeing through glass	Yes	Yes	No
Identification	Yes	Yes	No
Low thermal contrast scene	Long Range	Short Range	Limited
Resistance to parasitic light sources	High	Limited	-
Perform in rain, snow, fog	High	Low	Medium

Principle of active imaging can be implemented using two concepts. First concept is called gated imaging that uses typicaly pulse laser illuminator and the second concept is that in which continous wave laser illuminator is used [1], [2], [3].

The requirements for both system architectures, applicable for long range identification with SWIR/NIR active imaging systems, are elaborated and discussed. Current availability of systems components is reviewed and compared.

Goals that we had in this paper are to define system architecture for active SWIR imaging, functional analysis. In following sections comparison of pulsed gated and continuous irradiation is provided in order to define key components requirements.

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II. EYE SAFETY

Implementation of active imaging for many applications is limited by the requirement of eye-safety compliance. Visible wavelengths should be avoided which is disqualifying many mature solution that use visible range for imaging. In order to solve this problem, use of the visible wavelength band should be avoided.

Laser sources have been classified by wavelength and maximum output power into four classes and a few subclasses by the standard ANSI Z136 [4]. Laser classification categorizes laser sources by the ability to produce damage in exposed people, from Class 1 (no hazard during normal use) to Class 4 (severe hazard for eyes and skin).

SWIR spectral band is the best choice for implementation for active illumination due to eye safety properties of Class 1 laser sources that are emitting in this spectral range. A wide selection of high power laser types is available. For the camera high speed InGaAs focal plane array may be utilized for signal detection and conventional glass optics may be used, which gives possibility of large apertures long range SWIR system design.

Commercially available NIR active imaging systems use laser sources that are Class-4 laser source [5]. Manufacturers of such systems must provide caution measurements such as tools that are based on a variable laser power output and on a real-time Nominal Ocular Hazard Distance NOHD calculator.

III. ACTIVE IMAGING SYSTEM

A. *Active Gated Imaging System*

Active gated imaging system principle is based on a time of flight imaging technology [2]. The mechanism which is implemented in control electronics must provide synchronization between two time events: the moment of laser pulse emission and the moment when the camera opens/closes the shutter. The moment when the integration time Δt of the camera should be gated is the moment when reflected light pulse, which originates from laser illumination source pulse, is returned. This time can be calculated knowing the object distance d, as $\Delta t = 2d/c$, where c is speed of light.

Two parameters of active gated system are gate delay which is corresponding to the range to the target and gate width which defines the depth of observed scene containing the target. Principle of active gated system parameters is shown in Fig 1.

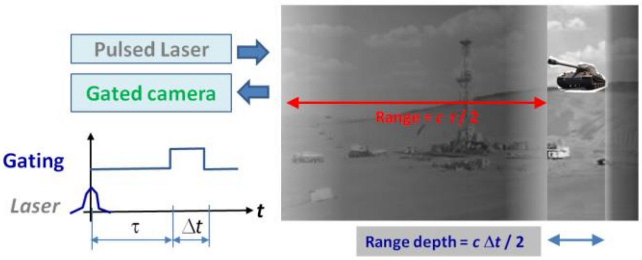

Fig. 1. Principle of gated imaging.

Using this technique, it is expected that image contrast will be enhanced comparing to passive imaging with the same sensor. Limitations of the achievable performance gain are in available laser power, repetition rate and pulse width and also the minimum controllable camera integration time.

B. *Active Imaging System with Continuous Illumination*

When designing a SWIR system for long range vision, zoom lenses with high focal lengths must be used. In that case the ratio of the aperture and the max focal length (known as F/# in system parameters notation) is increased. Increase in F/# is limiting the amount of light that is collected by the lens and visibility in low-light condition, through smoke, dust or fog. Passive imager is not capable of providing high contrast image. To obtain better visibility, active concept is used.

Continuous mode active systems can use standard InGaAs SWIR cameras available on the market and continuous mode laser illuminator since there is no limitation on minimum integration time of the camera.

Since laser illuminator is emitting light continuously, this concept is not recommended for NIR active systems which are using non eye safe laser source.

IV. SYSTEM ARCHITECTURE

Requirements for integration of gated active SWIR/NIR imagers into multi-sensor imaging system should be defined. To complete this task, first we analyze system parameters of the gated active couple (laser illuminator and camera) and then we are reviewing currently available products to see if they can fulfill these requirements.

A. *System Parameters*

The most important system parameters that are directly affecting the gain obtained with gated active system comparing to the passive mode solution are:

- Group of parameters referring to the camera:
  - minimum integration time and
  - sensitivity
- Group of parameters referring to illumination light source:
  - power of the emitted light from laser illuminator,
  - duration of the laser pulse, and
  - pulse repetition rate.
- Group of parameters referring to the gating control mechanism implementation:
  - minimum latency of the computing platform and
  - implementation of additional detection mechanisms needed for synchronization of laser pulse with camera start of integration.

B. *SWIR/NIR camera*

Wavelengths up to 1100 nm that are classified as NIR region, can be detected by newest generation image intensifier tubes, CCD and EMCCD sensors. Wavelengths of 1550 nm and 1625 nm are designed to be used with SWIR electro-optical systems. Cameras with InGaAs detectors are the leading technology for SWIR imaging, because of their high quantum efficiency and ability to operate at room temperature.

The requirement is posed to SWIR camera in terms of minimum obtainable integration time. The goal is to provide integration time as close to the width of laser pulse as possible. Also it is needed to have a good control of start time position and to minimize imaging outside the gated interval. Traditional Read Out Circuit ROIC design cannot always satisfy these requirements and new solutions are proposed [6].

Currently, on the market for SWIR cameras there are solutions which are offering integration time typically round 100 ns for QVGA and even lower than 100 ns for VGA resolution reported by one of the manufacturers.

For NIR cameras, it is possible to have minimum integration time as small as 40 ns, which is obtained in the system of coupled image intensifier with video camera that has resolution of image intensifier declared for 41 lp/mm.

In Table III data for minimum integration time are given for several commercially available SWIR/NIR cameras.

TABLE III
TYPICAL CHARACTERISTICS FOR SWIR AND NIR CAMERAS

Pixel size / resolution*	Spectral range	Minimum Integration Time [ns]	Frame rate [fps]
20 μm, QVGA	SWIR	100	400
15 μm, VGA	SWIR	200	100
13.4 μm, VGA	SWIR	70	30
(~12 μm) 41 lp/mm	Vis / NIR (image intensifier coupled with video camera)	40	60

* As camera resolution it is assumed 320 x 256 pixels for QVGA and 640 x 512 pixels for VGA.

C. *Selection of Light Source*

Active Imaging Scenarios can use continuous or pulsed illumination sources. Both options would be discussed in more details in sub-sections that follow.

D. *Continuous Illumination*

For illumination sources in SWIR band InP laser diodes are used for 1550 nm and 1625 nm wavelengths. In order to correct beam astigmatism, special micro acylindrical lenses are applied for long range imaging systems. Typical characteristics of a long range continuous laser illuminators are possibility to illuminate of distances up to 15 km with optical power up to 1.5 W and adjustable beam divergence from 1.5 mrad up to 40 mrad. SWIR band laser illuminators have significant safety advantage over NIR band ones since NOHD is much lower [3].

For NIR spectral range (915, 980 and 1064 nm) GaAs laser diodes are used as a light source. NIR band long range illuminator sources have maximum output powers up to 2 W and adjustable beam divergence from 1.5 mrad up to 40 mrad. Beam with 1.5 mrad divergence can provide illuminated diameter of 7.5 m at the distance of 5 km, and 15 m at the distance of 10 km. NIR band long range illuminators can be coupled with CCD or CMOS sensors and lenses with long maximum focal lengths (round 1000 mm) obtaining surveillance system which is fully capable of night vision. Such NIR band surveillance system can provide covertness to conventional night vision systems in military applications [3].

Ocular hazard distance NOHD value is 30 m at worst case scenario (high power mode, narrow beam) for SWIR band illumination, compared to 500 m for NIR band illuminators. In wide beam mode of 40 mrad NOHD of SWIR band illuminators drops down to 2 m.

Overview of typical characteristics of continuous illuminators operating in SWIR and NIR spectral band is given in Table IV.

TABLE IV
TYPICAL CHARACTERISTICS FOR SWIR AND NIR CONTINUOUS LASER ILLUMINATION SOURCES

Spectral range	SWIR 1550 nm 1625 nm	NIR 915 nm, 980nm, 1064 nm
Maximum output power	1.5 W	2 W
Minimum beam divergence	1,5 mrad	1,5 mrad
Minimum beam divergence	40 mrad	40 mrad
NOHD	30 m	500 m

E. *Pulsed Laser Source*

For design of laser sources in eye safe SWIR band there are currently three main technologies [7].

At 1.5 μm, Erbium-doped fiber lasers can achieve very high repetition rates round several MHz. But this technology still cannot be employed to get high energies / high average powers due to the setting up of strong nonlinearities [8].

Optical Parametric Oscillators OPO techniques are widely employed to convert the laser radiation from the near infrared part of the spectrum (at about 1 μm) to the 1.5 μm band. This technology enables high output powers / high repetition rates to be obtained. The main drawback of these systems is their low overall efficiency due to the nonlinear wavelength conversion (typical thirty percent conversion efficiencies). Moreover, the complexity associated with this multistage approach increases the number of components (driving cost) and makes design of a rugged, reliable package difficult. A laser source that directly emits eyesafe radiation could, in principal, be much less complex [8].

TABLE V
TYPICAL CHARACTERISTICS FOR SWIR AND NIR PULSE ILLUMINATION SOURCES

Laser technology	Fiber lasers	Solid State Laser with OPO	Solid State Laser
Operating wavelength	1.54 μm	1.57 μm	1 μm
Energy per pulse	20 – 350 μJ	0.8 mJ	4 mJ
Peak power	5 to 25 kW	Up to 400 kW	Up to 4 MW
Pulse duration	4 to 20 ns	< 2.5 ns	< 1.5 ns
Pulse repetition frequency	20 to 250 kHz	Up to 1 kHz	Up to 1 kHz

For wavelengths in the NIR band (round 1 μm), the most common pulsed lasers are based on a neodymium-doped laser crystal are used. A small actively Q-switched solid-state laser may emit 100 mW of average power in 10 ns pulses with a 1 kHz repetition rate and 100 μJ pulse energy.

The peak power is then ≈ 9 kW. The highest pulse energies and shortest pulse durations are achieved for low pulse repetition rates at the expense of somewhat reduced average output power. Larger Nd:YAG laser with a 10 W diode bar pump source can reach pulse energies of several mJ. Q-switched lasers with longer emission wavelengths are often based on erbium-doped gain media such as Er:YAG for 1.5 µm [9]. Also for NIR band there are mJ diode pulse illuminators available at the market.

There are also actively Q-switched solid-state bulk laser sources which directly emit eye safe radiation which are limited by the maximum obtainable repetition rate. [8]. Overview of typical characteristics of pulse laser sources operating in SWIR and NIR spectral band, that can be found at the market, is given in Table V.

F. *External Laser Pulse Sensor*

In order to provide detection of emitted laser pulse the device called External Laser Pulse Sensor LPS is designed. LPS should to provide information about LRF laser out coming pulse generation and pulse basic properties (pulse temporal shape, amplitude) without disturbing distance measurement process.

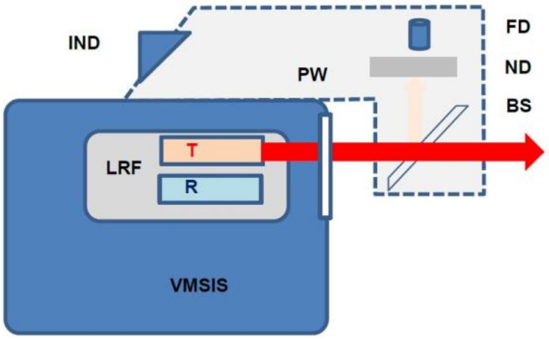

Fig. 2. Principle of Laser pulse sensor for initial of gating detection.

The proposed structure for LPS design is illustrated in Figure 2. Part of the generated laser pulse beam is extracted from measurement beam and redirected towards LPS receiver using beam splitter at 45 degrees in the LRF laser transmitter beam. Pending on beam splitter selection (glass plan parallel plate or AR coated glass plan parallel plate about 8 % or 0.5 % of laser pulse energy will be redirected towards receiver.

LPS comprises following key subsystems:

(1) Mechanical fixture

(2) Laser beam optical collection optics

(3) Laser pulse detection receiver

(4) LPS indicator

G. *The concept of signal processing electronics*

According to the basic principle of active gated imaging, illustrated in Fig 1.and assumed camera and laser characteristics given in Table III and Table V, a concept of signal processing electronics is assumed given in Fig 3.

As a camera video interface we have assumed Base Camera Link standard [10] which specifies transmission of 28 bits of data at pixel clock rate. At physical layer these 28 bits are transmitted by four parallel lanes at 7 times higher data rate giving maximal distance between camera and signal receiver (frame grabber) up to 10 m. From these 28 bits, 24 are used for transportation of pixel value, which in SWIR camera case corresponds to pixel illumination. Typically illumination signal is digitized from 10 to 14 bits, so unused bits are neglected. Remained four bits are used to transmit signals: frame valid, line valid, data valid and spare. Signal *frame valid* is active only once per frame, so it is used for synchronization of circuitry for generation pulses for triggering laser pulse and after delay equal to τ camera integration triggering.

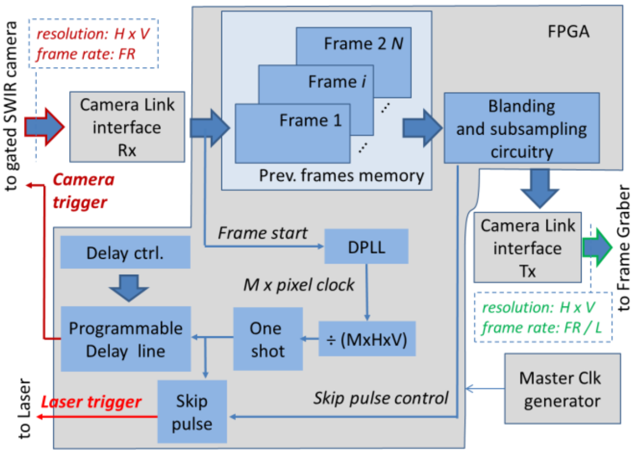

Fig. 3. Control system for gated SWIR camera

The assumed technology for signal processing implementation is Field Programmable Gate Array FPGA. Since pixel clock rate at Camera Link interface is up to 85 MHz, which corresponds to delay resolution of 11.7 ns. This is not sufficient for accurate delay adjustment. Thus Phase Locked Loop PLL circuitry for clock multiplication by factor *M* is needed which operates at externally generated master clock. The value of factor *M* is up to 8 which gives sufficient resolution which is close to laser pulse width (~1 ns). The blocks that follows are: one shot and programmable delay line which are easily implemented by FPGA logic.

Since gated SWIR cameras can operate at frame rate higher than usual surveillance frame rate of 25 or 30 fps, this fact could be exploited for advanced processing. For cameras in Table 3, sub-sampling ratio *L* could be up to 16. One example of such processing is depth scanning by data fusion between several adjacent frames which is simple achieved by averaging pixel values at coordinates (*a*,*b*) between adjacent frames. This functionality is performed by blending and sub-sampling circuitry.

Additionally, effect of reducing clutter introduced by background illumination, could be reduced by simple subtraction of two adjacent frames from which one is shot with laser illumination, while the other is shot without it. For this application, skip pulse logic is added which is controlled by blending and sub-sampling circuitry. Effects of such processing are investigated in [11], and promising results were reported. Unfortunately, the authors used low end FPGA, so only two adjacent frames are taken into consideration. In this design we assume processing of up to 16 adjacent frames. This would require previous frame memory capacity of about 12 MB for resolution 640 x 512 pixels, which is available in FPGA logic.

V. EXPECTED PERFORMANCE GAIN

There are reported experimental data of an eye safe SWIR active system in which are achieved range measurements and successful people recognition tasks at up to 5 km, that are confirmed also with prediction modeling [12].

Modeling of SWIR active system performance should take into account various propagation effects and important parameters that are affecting active gated imager performance like:

- Target characteristics (size, reflectivity, position)
- Laser beam characteristics
- Environmental conditions (atmosphere parameters)
- Sensor and optics characteristics (sensitivity, FOV)

Predictions for a long range system performances that are reported in literature [12] are very promising as calculation using the implemented model and Johnson criteria are recognition with 90 % accuracy of large vehicle (10 m x 3 m) at 10 km. Such result would be adequate for application in long range surveillance system.

VI. CONCLUSION

It is shown that active SWIR systems significantly contribute in a task of identification of small targets in low light and under atmospheric disturbance conditions and that they should be used as additional channel in a multi-sensor imaging system for border and coastal protection. An elaboration of modules used in active gated SWIR and NIR systems is given. It is explained that, for the eye safety issue, these systems are preferably realized in SWIR spectral band, especially if their application is required in urban and populated area. The principle of gated vision is explained and all components of the systems are discussed and important system parameters are reviewed. Additional concept of control electronics is presented and explained, as well as accessory modules for detection of laser pulse sent from laser source that initiate active gating imaging event.

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