Range Performance Modelling and Estimation for Uncooled Monocular Thermal Imagers

Abdulrahman Alsalmi
King Saud University
Saudi Arabian Military Industries Company (SAMI)
Riyadh, Saudi Arabia
a.alsalmi91@gmail.com

Ahmed Almaiman
King Saud University
Riyadh, Saudi Arabia
ahalmaiman@ksu.edu.sa

Mohammed Ramy
King Saud University
Riyadh, Saudi Arabia
mohamedramy@gmail.com

***Abstract*— A theoretical model for predicting the range performance of a monocular thermal imager (MTI) is developed in this work. System MTF for an MTI is derived and then detection, recognition and identification (DRI) ranges were calculated using Targeting Task Performance (TTP) model. Current mainstreamed as well as futuristic detector and micro-display pixel side lengths are considered in MTF analysis and DRI range calculations. DRI ranges are estimated to be improved when smaller detector and micro-display pixel side lengths are employed. Numerical simulations show that DRI ranges can reach 26.757, 5.95, 4.12 km for an MTI with detector and micro-display pixel side lengths of 5µm each.**

Keywords— Monocular Thermal Imager, Range Performance Modelling, Modulation Transfer Function

I. Introduction

Theoretical predictions of the detection, recognition and identification (DRI) ranges of thermal imagers are of great importance for the developers and users of thermal imagers. Night Vision Integrated Performance Model (NVIPM) [1] and (European Computer Model for Optronic System Performance Prediction) TRM4 [2] softwares are used for predicting the range performance of typical thermal imagers. NVIPM and TRM4 are not easily accessible softwares. In addition, NVIPM and TRM4 do not possess the ability of modeling monocular thermal imagers (MTIs), where an MTI is a variant of a typical thermal imager yet has additional hardware components: micro-display and viewing eye-piece.

The main aim of this work is to develop a theoretical model for predicting the range performance of an MTI. The range prediction method will be based on deriving an expression for the MTI's modulation transfer function (MTF) and then applying the theoretical range prediction methodology of the Targeting Task Performance (TTP) model [1]. In this work, a standard NATO tank target will be used for the analysis and two main variants will be introduced during the range prediction analysis: the detector and the micro-display pixel side lengths. The MTF analysis and range performance will be performed for MTIs with detector pixel side lengths ranging from 25µm to 5µm and with micro-display pixel side lengths of 15 and 5µm; thus, providing analysis results for existing technologies and future technologies with expected miniaturization advancements in detector and micro-display pixel sizes.

II. System Description

An MTI system consists of the following subsystem components: infrared imaging optics, detector focal plane array, signal processing electronics, a micro-display and an eye-piece. Finally, a viewing human eye will be looking at the image though the eye-piece. Fig.1 shows a conceptual depiction of an MTI system.

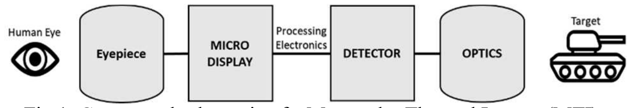

Fig.1: Conceptual schematic of a Monocular Thermal Imager (MTI).

The system MTF of a MTI can be calculated by multiplying the MTF of the subsystem components.

The MTF for circular optics is [3]:

$$MTF_{Optics} = \frac{2}{\pi}\left[\cos^{-1}\left(\frac{u}{u_{co}}\right) - \frac{u}{u_{co}}\sqrt{1-\left(\frac{u}{u_{co}}\right)^2}\right] \quad (1)$$

where $u_{co} = D_o/\lambda$ is the spatial cut-off frequency. D_o being the diameter of the infrared optics aperture in mm, λ is the wavelength in µm, and u has units of cycles/mrad. In this work, D_o is chosen to be 48mm and λ is 10µm. The detector MTF is given by [3]:

$$MTF_{Detector} = \left|sinc(\pi\alpha_d u)\right| = \left|\frac{\sin(\pi\alpha_d u)}{\pi\alpha_d u}\right| \quad (2)$$

where α_d is the ratio between detector side length (d_d) and the focal length of the infrared optics, $\alpha_d = d_d / f_o$. In this work, f_o is chosen to be 60mm and d_d will be varied from 25µm to 5µm. The focal plane array fill factor is assumed to be 100%. Further, the MTF of signal processing electronics is assumed to be 1 at all spatial frequencies. The micro-display's MTF is given by [4]:

$$MTF_{Micro-display} = \left|sinc(\pi\alpha_{md} u)\right| = \left|\frac{\sin(\pi\alpha_{md} u)}{\pi\alpha_{md} u}\right| \quad (3)$$

where α_{md} is the ratio between pixel side length (d_{md}) and the focal length of the eyepiece $\alpha_{md} = d_{md} / f_e$. In this work, f_e is chosen to be 24mm and d_{md} will be taken as 15µm and 5µm. The micro-display array fill factor is assumed to be 100%. The eye-piece MTF is given by [4]:

$$MTF_{Eye-piece} = \frac{2}{\pi}\left[\cos^{-1}\left(\frac{u}{u_{ce}}\right) - \frac{u}{u_{ce}}\sqrt{1-\left(\frac{u}{u_{ce}}\right)^2}\right] \quad (4)$$

where $u_{ce} = D_e / \lambda_e$ is the spatial cut-off frequency. D_e being the diameter of the eyepiece optics aperture in mm, and λ_e is the wavelength of the visible viewing light in µm. In this work, D_e is chosen to be 22mm and λ_e is 0.55µm.

The MTF of the system is the multiplication of all of the subsystem MTFs and is given by:

$$MTF_{Monocular} = MTF_{Optics} \times MTF_{Detector} \times MTF_{Micro-display} \times MTF_{Eye-piece} \quad (5)$$

III. Results & Descussion

Figure 2 depicts detector MTF versus spatial frequency for detectors having d_d of 25, 17, 12 (current mainstreamed d_ds),10 and 5µm (emerging and futuristic d_ds). It can be observed that smaller detector dimensions yield higher spatial cutoff frequencies which implies that more scene details can be resolved with smaller pixel sizes.

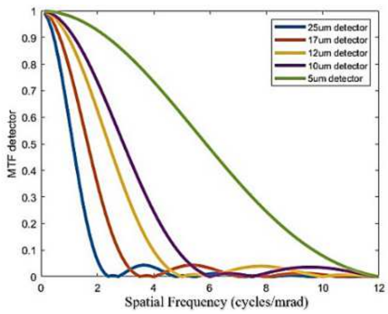

Fig.2: Detector MTF vs. spatial frequency for detectors with different d_d

Optics, micro-display and eye-piece MTFs are not plotted for briefness. However, for the selected D_o and λ, optics MTF shows a cutoff frequency of 4.8 cycles/mrad. This MTF response of a monocular system having d_d of 12, 10 and 5µm will be limited by optics. Micro-display MTF follows the same behavior of detector MTF. The cutoff frequencies for micro-displays with 15 and 5µm pixel sizes are 1.6 and 4.8 cycles/mrad, respectively. MTF response of MTIs with d_d of 10 and 5µm would be limited by micro-display having pixel side length d_{md} of 5µm. And MTF response of MTIs with $d_d >$ 10µm would be limited by micro-display having pixel side length d_{md} of 15µm. Moreover, the spatial cutoff frequency for eyepiece MTF is found to be 40 cycles/mrad for the selected D_e and λ_e; eye-piece has no effect on system's MTF response.

Fig.4 and Fig.5 shows the system MTFs for monoculars having mico-displays with of 15µm and 5µm pixel side lengths respectively. As expected, monoculars with smaller d_d and d_{md} show higher spatial cutoff frequencies which will translate into higher DRI ranges.

The calculation of DRI ranges is done based on the TTP metric model and is calculated using the following equation [1]:

$$Range = \frac{W\sqrt{C_{TARGET}}}{V} FOM \frac{D_o}{\lambda} \quad (6)$$

where W is the target effective size which is chosen to be 3.1m, the effective size of a standard NATO tank target, and V is the task difficulty. V = 2, 9 and 13 for 50% probability of detection, recognition and identification respectively [3]; C_{TARGET} is given by [1]:

$$C_{TARGET} = T_{ATM} \frac{1}{2} \frac{\Delta T}{SCN_{TMP}} \quad (7)$$

where C_{TARGET} is the apparent target contrast, T_{ATM} is the atmospheric transmittance and is taken as 0.8. ΔT is taken to be 1K and it represents the contrast difference between the target and the scene. SCN_{TMP} is the scene contrast; SCN_{TMP} of 25K is used in this analysis. FOM (Figure of Merit) is given by [3]:

$$FOM = \int_0^{u_n} \sqrt{\left| \frac{MTF_{System}(u)}{CTF_{Eye}(u)} \right|} du \quad (8)$$

where CTF_{Eye} is the contrast transfer function of the human eye and u_n is the Nyquist frequency [1]. The calculated DRI ranges are given in Table.1.

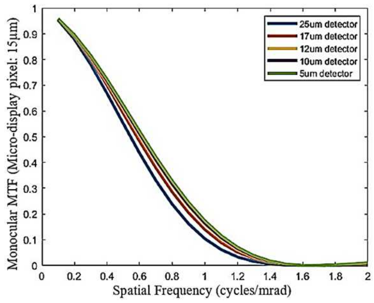

Fig.4: Thermal monocular MTF at various detector pixel size lengths and micro-display pixel size length of 15µm

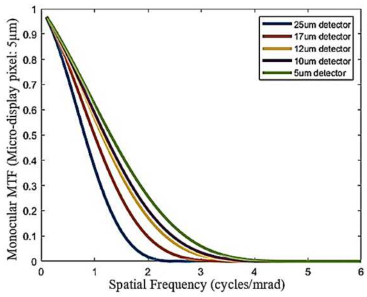

Fig.5: Thermal monocular MTF at various detector pixel size lengths and micro-display pixel size length of 5µm

Table.1 Calculated DRI Ranges

Calculated DRI Ranges				
Micro-display pixel side length (µm)	Detector pixel side length (µm)	Detection Range (km)	Recogni-tion Range (km)	Identifi-cation Range (km)
15	25	4.09	0.91	0.63
	17	6.34	1.41	0.98
	12	6.74	1.50	1.04
	10	8.88	1.97	1.37
	5	9.12	2.03	1.40
5	25	6.05	1.34	0.93
	17	11.82	2.63	1.82
	12	15.9	3.53	2.45
	10	22.83	5.07	3.51
	5	26.757	5.95	4.12

IV. Conclusion

In this paper, a mathematical model is developed to predict DRI ranges of an MTI. MTF responses of subsystem components are derived and analyzed. MTIs with d_d of 25, 17, 12, 10, and 5um and having d_{md} of 15 and 5um were studied. DRI ranges were calculated for all 10 scenarios utilizing the TTP model. The study showed that MTIs with smaller d_d and d_{md} possess better MTF responses and thus higher DRI ranges.

References

[1] R. H. Vollmerhausen and E. Jacobs, "The Targeting Task Performance (TTP) Metric A New Model for Predicting Target Acquisition Performance," NVESD Technical Report AMSEL-NV-TR-230, Fort Belvoir, VA (2005).

[2] Keßler, S., Gal, R., & Wittenstein, W. (2017). TRM4: Range performance model for electro-optical imaging systems. *SPIE Proceedings*.

[3] G. C. Holst and R. G. Driggers, "Small detectors in infrared system design," *Optical Engineering*, International Society for Optics and Photonics, 13-Sep-2012.

[4] V. H. Kolobrodov, "Modulation transfer function of the thermal imaging monocular," *Visnyk NTUU KPI Seriia - Radiotekhnika Radioaparatobuduvannia*, no. 78, pp. 74–78, 2019.