Super-resolution imaging using patterned illumination

Seeing “more” with unmatched clarity

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Motivation
U.S. forces are often immersed in hostile environments ranging from broad open spaces to cluttered urban environments. The wide variety of threats encountered in these environments places exacting demands on optical S&R (Surveillance and Reconnaissance) systems to gather actionable intelligence. The design of such systems is complicated by the need to accommodate
- multiple platforms such as Unmanned Aerial Vehicles or crawling robots or rooftop installations
- day/night operation under harsh conditions
- wide-field (WFOV) situational awareness & narrow-field (NFOV) target identification capabilities.

Current S&R systems are the product of a complex tradeoff between SWaP (size, weight and power) and the capabilities of the constituent components, which include active/passive electro-optic (EO) imagers. Although active and passive imagers acquire light across a broad swath of the electromagnetic spectrum, the active variants use a dedicated illumination source to maximize the recovery of object information (intensity, range, phase, velocity, detecting vibrations) from the backscattered light. A second benefit of active EO sensing is the ability to operate in complete darkness, and the support for gated viewing which enables long-range operation and seeing through obscurants.

The breadth of information that can be identified using active EO sensing has resulted in an explosion of military and commercial interest. A simultaneous increase in global academic activity in the area is evidenced in the publication count, especially from China [1]. A recent report by NAP [1] observes that easy access to diode/solid-state laser illuminators, increasingly sensitive detectors and cheap computing power, has reduced the tactical advantage enjoyed by U.S forces. The report strongly recommends the pursuit and development of active EO sensing technologies.

Challenge
In an effort to further improve the tactical advantage of US forces, the described research effort tackles a longstanding problem in S&R: **target/threat detection and identification at increased standoff, in a wide field of regard, with the highest clarity, in complete darkness and through the cover of obscurants.** Addressing the problem calls for the development of a system that supports
1. foveated imaging + ranging at resolutions exceeding the aperture-diffraction and detector limits
2. imaging across multiple wavebands (spectral sensing)
3. active illumination for operation in complete darkness, and
4. gated viewing for long-range operation and seeing through obscurants

Realizing these capabilities while minimizing SWaP is the principal objective of the described research effort. It calls for a series of innovations in the EO imaging chain. The first of these innovations involves circumventing the fundamental limits imposed by the wave nature of light, a task referred to as Optical Super-Resolution (OSR) in subsequent discussions.

Innovation-1: Optical Super Resolution
With DoD funding, the Photonics group at SMU developed novel computational imagers whose resolving power is fully decoupled from the constraints imposed by the collection optics (such as diffraction and aberrations) and the detector (varying degrees of aliasing ranging from single photodiode to focal plane array). Equally attractive features include support for foveated imaging and ranging, in a variety of mono-static and bi-static arrangements. Results compiled from various experiments are tabulated in Figure 1. Details pertaining to each experiment and associated Spatial Frequency Response (SFR) plots are available in Chapters 6 & 7 of [2]. Under laboratory settings,
resolution gains in excess of $4 \times$ diffraction limit, and sub-mm range resolution over $1.1 \text{ m}$, were achieved.

The combined ability to range & super-resolve, accommodate aberrations & aliasing, and support for foveated imaging are capabilities that are unique to our work.

Figure 1 Select experimental results that highlight the capabilities of SMU’s active computational imager. Please note that in each example the super-resolved image contains spatial detail past the diffraction limit of the collection optics.
The dual objectives of surpassing the diffraction limit and ranging, are realized by processing images acquired under spatially patterned illumination (such as sinusoids or lattice of light spots). The Moiré fringes arising from the heterodyning of object detail and patterned illumination encapsulate spatial frequencies lost to optical blurring. The deformations in the phase of the detected illumination pattern, encode range information. These concepts are illustrated in Figure 2. The modulation diversity afforded by phase-shifting the illumination pattern helps restore the heterodyned spatial frequencies and recover range information, in an unambiguous manner. The reader is referred to [2] for a complete discussion of these mechanisms.

Super-resolution using lattice illumination has a simpler interpretation. It is observed that the illuminated object resembles a collection of point-like objects whose spacing exceeds the two-point resolution of the imaging optics. Following optical blurring, light from each illuminated object spot is distributed over one or more pixels. By reintegrating the distributed light, we can decouple the imager resolving power from the constraints imposed by the collection optics and the detector. Figure 3 illustrates the concept for a single spot in the lattice.

The discussion thus far has not identified the resolving power of our computational imager. In the absence of atmospheric turbulence, it is observed that the resolving power is limited only by the feature size of the illumination pattern. We circumvent the need for a WFOV pattern projection system with exacting spot size requirements, by using a beam scanning apparatus and a NFOV illuminator. The concept is illustrated in Figure 4. A variant of the arrangement [3] helped produce the results in Panels 3 & 4 of Figure 1. It should be noted that independently operating beam scanning arrangements can simultaneously observe multiple targets.

The configuration of Figure 4 bears a striking resemblance to scanning units in a variety of active EO sensors such as LADAR, and gated-viewing imagers in S&R systems. The principal difference is the use of spatially patterned illumination, instead of uniform illumination. It is envisioned that the capabilities of many active EO sensors can be augmented to acquire high resolution imagery, with suitable modifications.

The configuration of Figure 4 shares another similarity with S&R systems, namely FOV steering. State-of-the-art S&R systems employ a WFOV imager for situational awareness, and a NFOV imager for long-range identification. An arrangement of mirrors or Risley prisms is typically used to steer the field of view of the NFOV imager within the wider field of regard. In view of this similarity, it is envisioned that the NFOV imager in current

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**Figure 2** Observation of Moiré fringes and phase deformations in a bi-static configuration

**Figure 3** OSR using lattice illumination

**Figure 4** Super-resolving a region of interest in a wide field of regard using beam steering
S&R systems may be replaced with a laser illuminator with comparable resolving power. The principal advantage of this transition is the ability to interrogate the field of regard at multiple scales or resolutions (please refer to Panel-4 in Figure 1 for an illustration of the concept), in an adaptive and task dependent manner. Such capabilities are rarely supported by current S&R systems.

The resolving power of the concept imager described in Figure 4 is limited by the waist-diameter of the propagating Gaussian beam. In select NFOV target identification tasks, it may be required to exceed this limit. Clues to circumventing the limit emerge in a comparison of the smaller central lobe width of higher order resolutions, with their Gaussian counterparts.

Innovation-2: Engineered optical beams

The second innovation centers on the ability to squeeze light into a region smaller than the diffraction limit. Although literature is rife with examples of such approaches, we restrict our attention to a superposition of LG modes [4], whose cross-section remains unchanged over extended propagation distances. Squeezing light into a region smaller than the diffraction limit produces side lobes that greatly reduce the light throughput of the central spot. These side lobes also corrupt the optical image of a single illuminated object spot, limiting the success of our super-resolution strategy. Preliminary analysis suggests that increasing the spacing between the side lobes and the central lobe ($R$ in Figure 5) beyond the two-point resolution of the collection optics, will allow us to isolate the contribution of the central spot from the side-lobes, at the detector. The imager concept is illustrated in Figure 5. It is observed that the resolving power of such imagers is limited by the spot diameter of the central lobe of the illuminated spot, and its light throughput.

In summary, engineered optical beams have the potential to create tightly confined spots and well separated side lobes. The former is useful for computational resolution enhancement, whereas the latter avoids coupling light into the image of the central spot. Both achievements come at the expense of SNR, since an appreciable amount of light energy is allocated to the side lobes.

Limitations

The approach discussed thus far is not without limitations, chief of which is the loss of temporal bandwidth. In [5], we devised an optimization strategy for minimizing the number of temporal observations needed to realize a prescribed gain in the resolving power of a diffraction limited imager. The strategy draws inspiration from recent work in identifying sparse/compressible solutions to linear systems. Its scope however is limited to imagers with space-invariant blur. In order to accommodate a broader class of imagers characterized by spatially varying blur, we devised a second strategy [3] that relies on the use of lattice illumination to sparsely sample the object field, whereupon established interpolation techniques are used to assemble the super-resolved image from fewer observations than required for perfect reconstruction. The effectiveness of this strategy is apparent in Panel-4 of Figure 1, where in the super-resolved image was assembled using 50% of the observations. It is anticipated that a further reduction is possible by adapting sparse-signal reconstruction schemes, to our task.
The second limitation concerns the degradation in image quality arising from the speckle due to atmospheric turbulence and surface roughness. The former is typically mitigated by a combination of gated viewing and temporal averaging over multiple observations. The latter is typically mitigated by using broadband illumination. Due to our limited experience in coping with such degradations, we will seek to partner with vendors and research groups with extensive experience in these areas. A preliminary study will simulate turbulent conditions on an optical table, by using a hot griddle.

The final limitation is the increased range uncertainty and possible loss of range resolution, at longer standoffs. These are attributed to insufficient phase deformations in the detected illumination pattern. In such cases, ranging using the time of flight (ToF) principle may be used to yield reliable estimates.

**Main challenges**

- Optimization of engineered optical beams to maximize resolution gain and target irradiance
- Investigate the effect of turbulence on super-resolution strategy and engineering optical beams

**SNR requirements**

<table>
<thead>
<tr>
<th>Assumptions</th>
<th>Highly portable S&amp;R platform</th>
<th>Short range S&amp;R platform</th>
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<tr>
<td>Wavelength</td>
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<td>$\lambda = 532 \text{ nm}$</td>
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<tr>
<td>Daylight operation</td>
<td>$\text{photon flux} = 10^{10} \text{ photons sec}^{-1} \text{cm}^{-2}$</td>
<td>$\text{photon flux} = 10^{10} \text{ photons sec}^{-1} \text{cm}^{-2}$</td>
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<td>Illumination pattern</td>
<td>lattice of light spots (identical power in each spot)</td>
<td>lattice of light spots (identical power in each spot)</td>
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<td>Design Parameters</td>
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<tr>
<td>Standoff distance</td>
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<td>$100 \text{ m}$</td>
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<tr>
<td>Transverse resolution</td>
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<td>$1 \text{ mm}$ (on object)</td>
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<tr>
<td># spots</td>
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<td>$500 \times 500$</td>
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<tr>
<td>Power of light source</td>
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<td>$SNR = 10^3$</td>
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<td>$&lt; 1 \text{ mW}$ (with spectral filter)</td>
<td>$100 \text{ mW} - 1 \text{ W}$ (with spectral filter)</td>
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**Technology development path**

The imaging and ranging solution discussed in this response is a high risk/high payoff undertaking. It builds on the novel class of computational imagers being developed at SMU. Due to its originality there are multiple open questions that can only be answered during development. We would seek to develop proof-of-concept prototypes that address the technical risks and demonstrate the efficacy of the concept imager. These would be initiated with an optical table top demonstration in the visible and work towards longer wavelengths.

**References**


