



SPAD-Based Optical Camera Communications in a Warehouse Application

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Presentation Overview

Motivation & Background

What is Optical Camera Communications?

System Design

Warehouse Deployment

Key Findings

Future Work

Conclusion





Motivation & Background

Current state of logistics industry –
Limited automation opportunities and inefficiencies

Motivation & Background



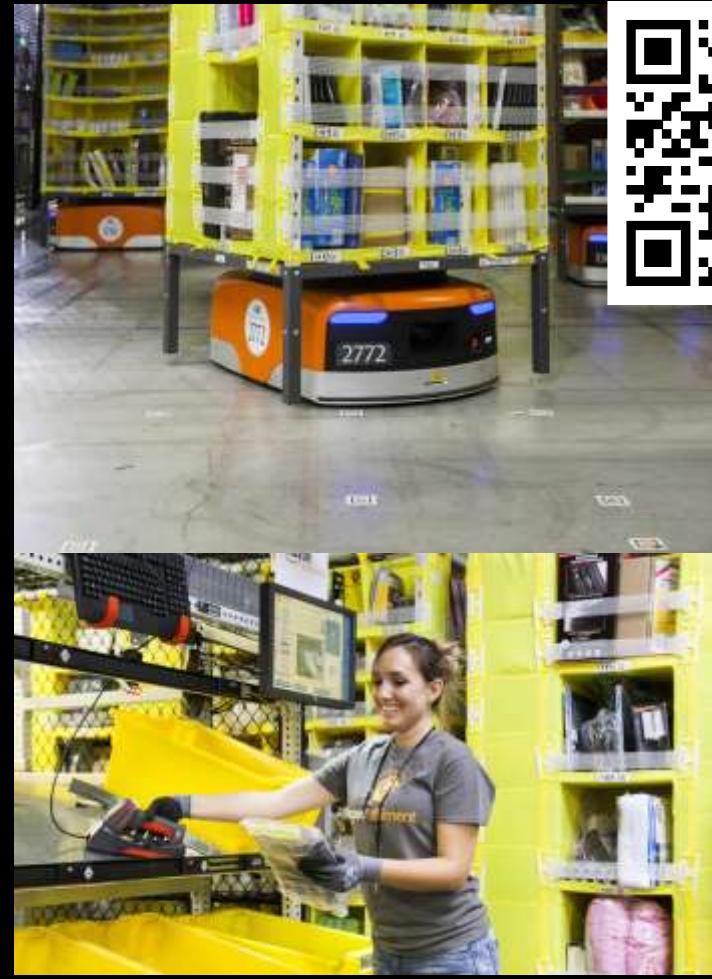
Robots localize using QR or camera tracking (slow)

- Frequent stopping to read QR codes
- Malfunctioning hardware easily causes excursions (limited localization rate unable to correct for malfunctions)
- Limited top-speed for CV-based camera tracking

Motivation & Background

Barcode-based system for picking items slow and error-prone

- Worker searches for item based on description, only verified by scanning item barcode
- Requires external database tying barcode to item data



Motivation & Background

For inventory checking, manual scanning and inspection of stock status is required

- Lack of remote interface & live data
- Worker must manually locate and inspect stock





Existing Technologies Have Trade-Offs

RFID: Limited range & coarse localization capability

Barcodes: Low data rate, manual scanning

Radio-location (GNSS, BLE): Poor indoor precision, cost & battery life

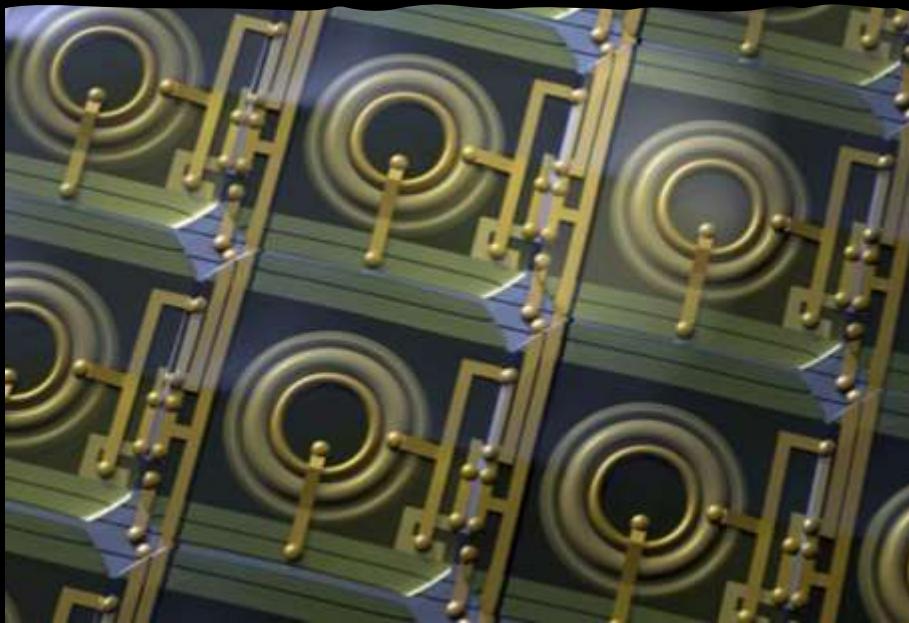
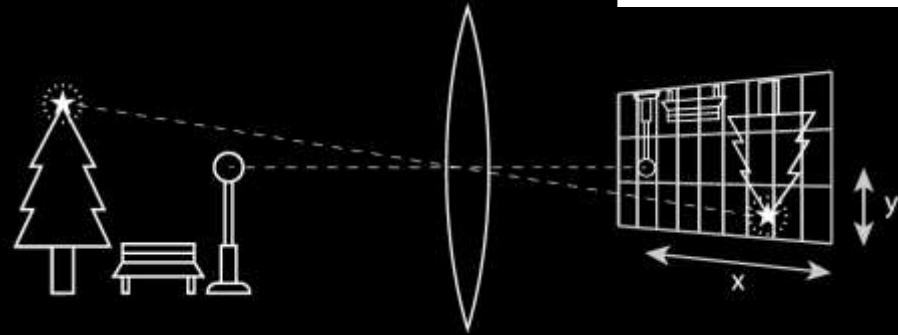
Our Solution – Optical Camera Communications:
Optical Data Communication + Localization

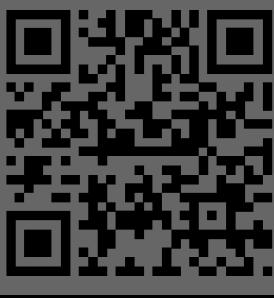


Optical Camera Communications



- Optical form of space-division multiple access (SDMA)
- Fine spatial resolution using light (compared to RF)
 - Each pixel simultaneously acts as a receiver beam
- Single-photon avalanche diode (SPAD) sensors detect single photons with nanosecond precision
 - Enables high-rate communication and localization with minimal optical power input



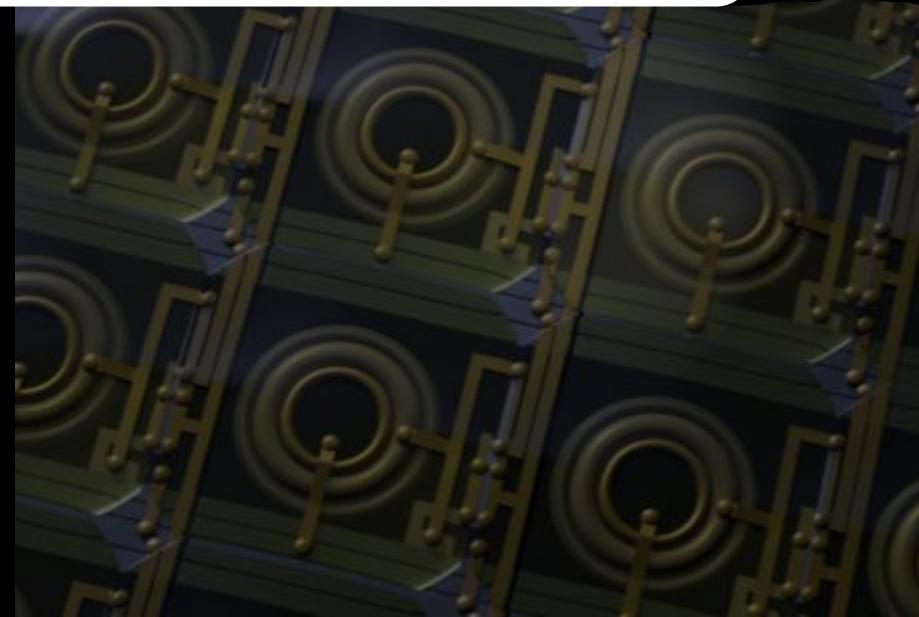
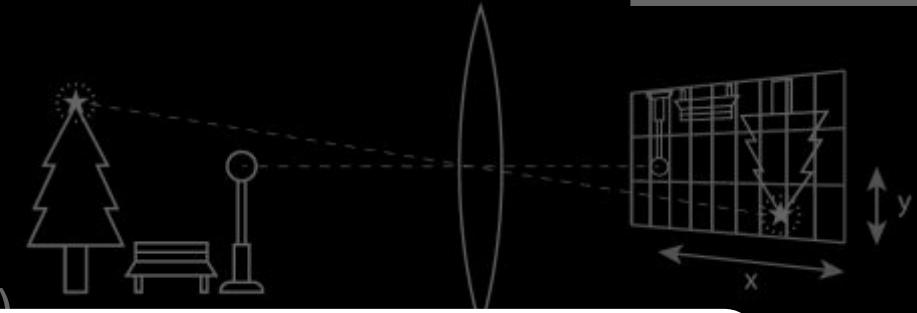


Optical Camera Communications

- Optical form of space division multiple access (SDMA)

Data rate: Up to 30 Mbps/stream OOK with current SPAD sensors
Localization Precision: <5 cm (depending on distance)

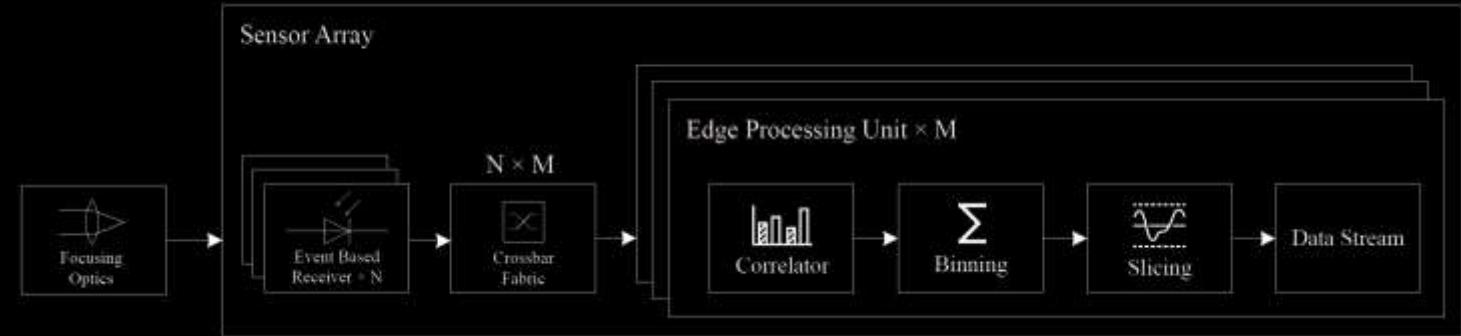
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System Design (Receiver)

- On-sensor edge processors
- SPAD receiver
 - Frameless sensing
- Pixel crossbar & tracking
 - Seamless pixel switching

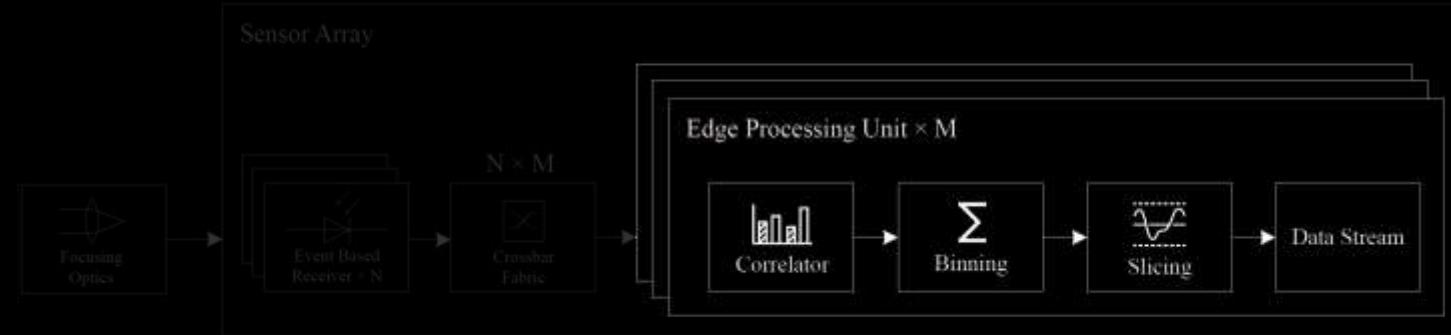




System Design (Receiver)

On-sensor edge processors

- Implements baseband and demodulation/decoding capability
 - Can be simpler due to OCC channel guarantees
- As many edge processors as the number of desired simultaneous streams

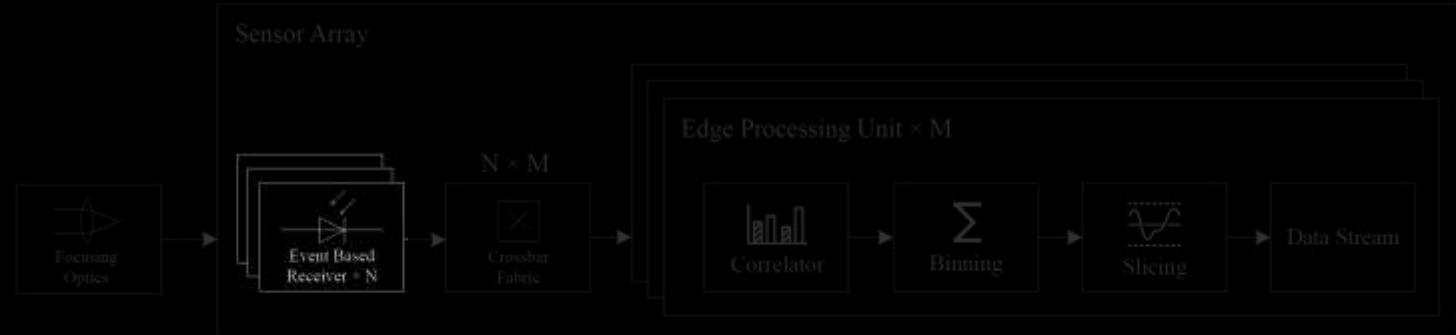




System Design (Receiver)

SPAD receiver

- 512x512 resolution
- Frameless sensing
- Photon arrival events
- No frame accumulation / integration time

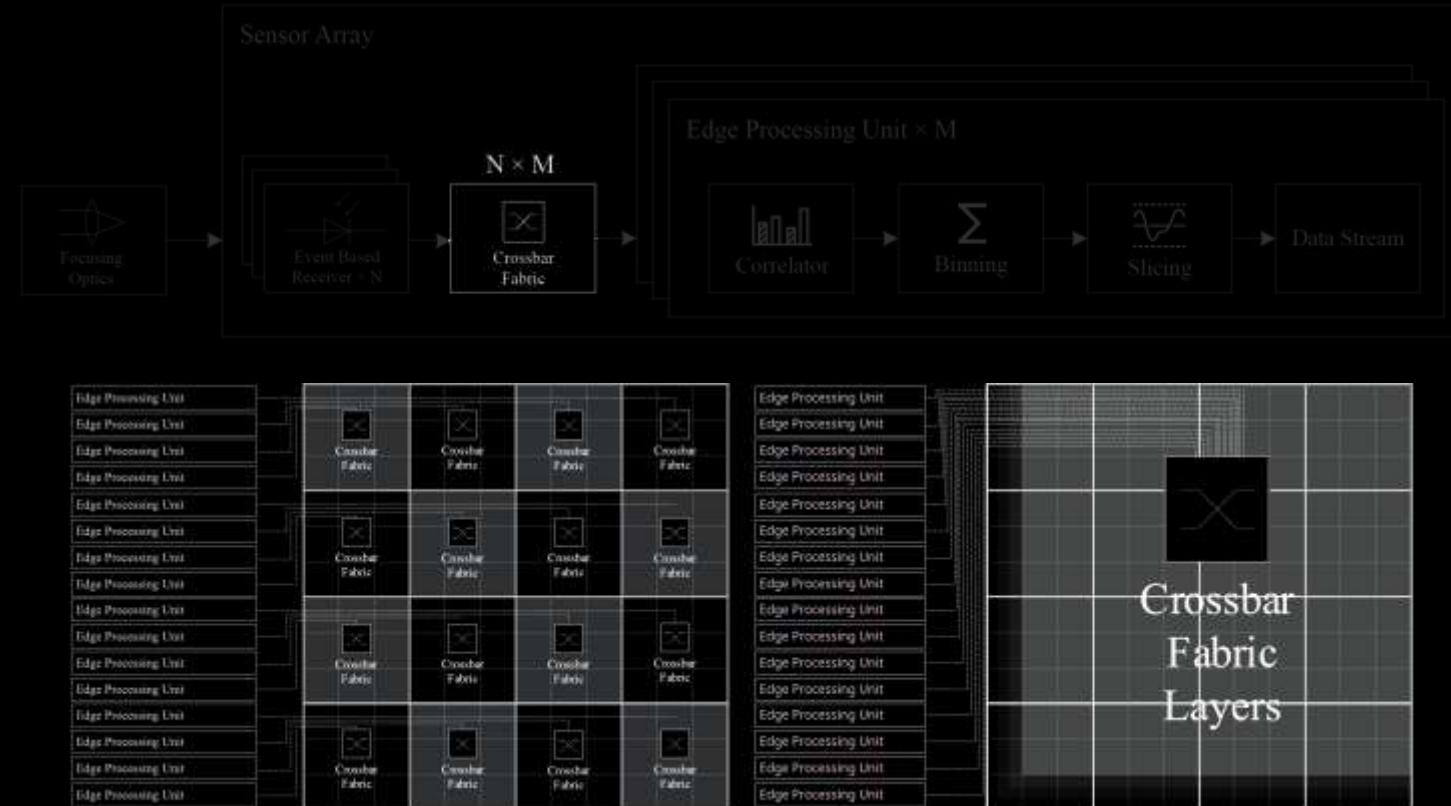




System Design (Receiver)

Pixel crossbar & tracking

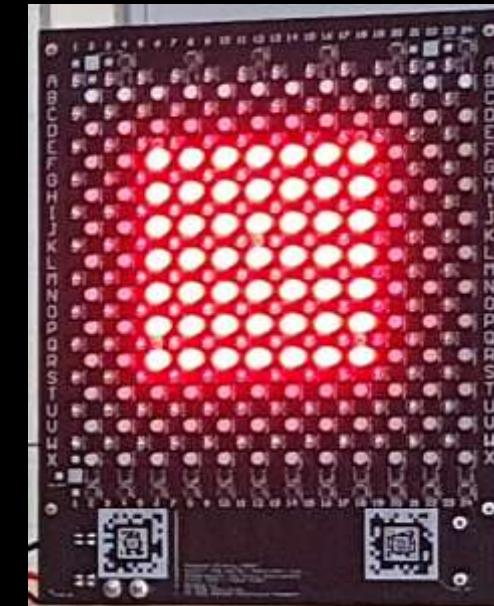
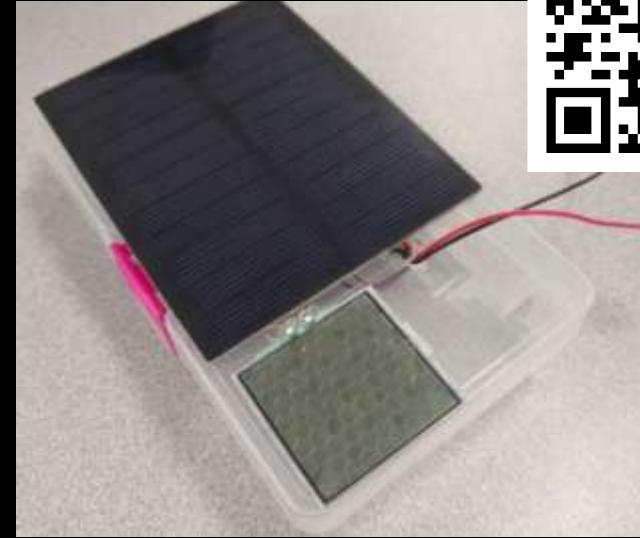
- Attaches individual or groups of SPAD pixels to edge processing unit
 - Different crossbar configurations possible with trade-offs
- Crossbar controlled via software, tracking algorithms required to predict movement of transmitters





System Design (Transmitters)

- Passive tags powered via ambient & interrogation light
 - Modulates incoming light using LC shutter and retroreflector surface
- Active anchors mounted to & powered by infrastructure
 - High speed data
 - Reference anchor points for localization



Warehouse Deployment



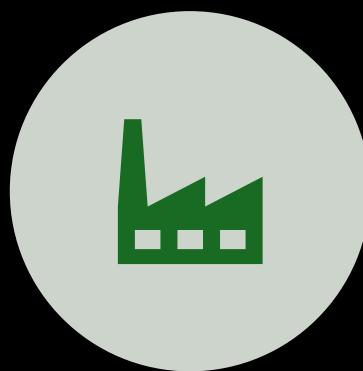
- Collaboration with Kuehne+Nagel (K+N) under NOL Fellowship Programme
- Deployment of OCC system for three use cases



INVENTORY
TRACKING



WORKER
MONITORING

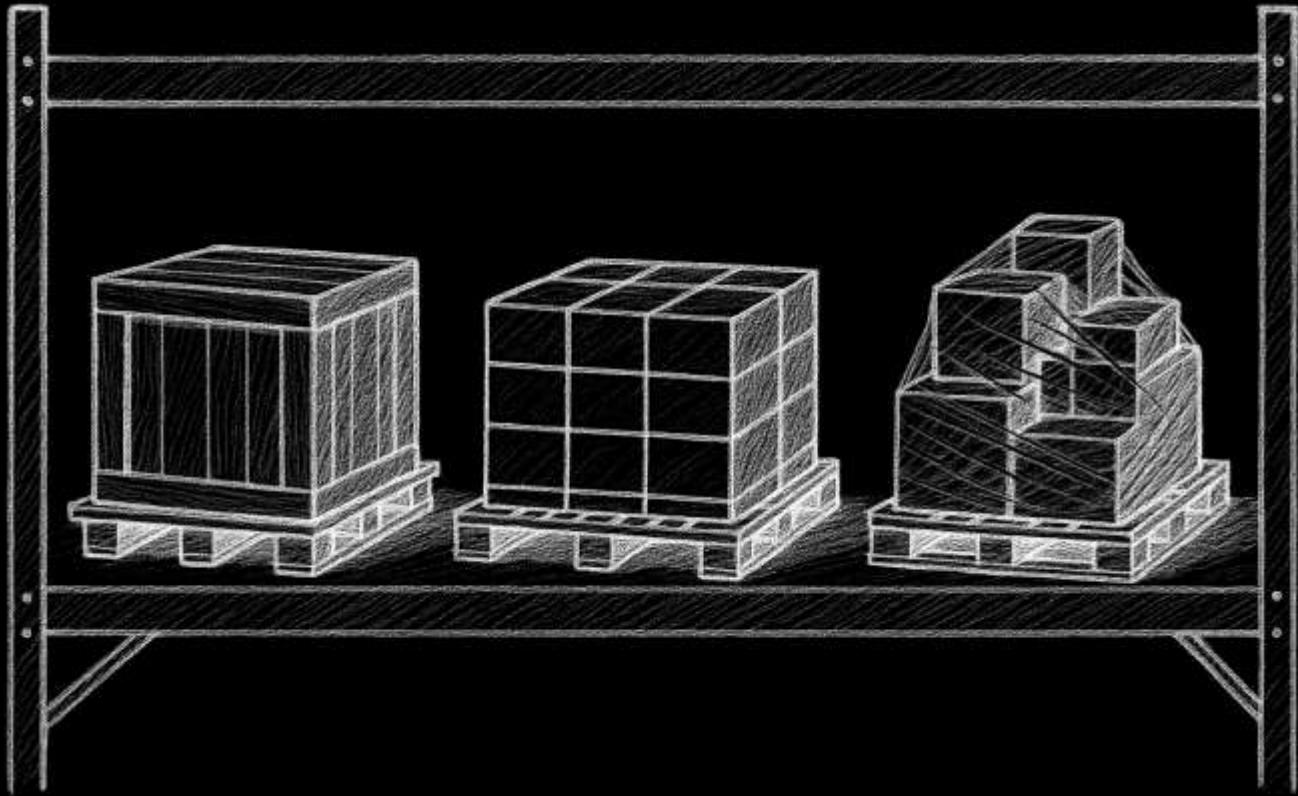


WAREHOUSE
AUTOMATION



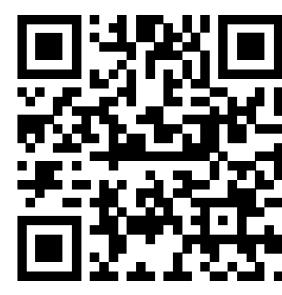
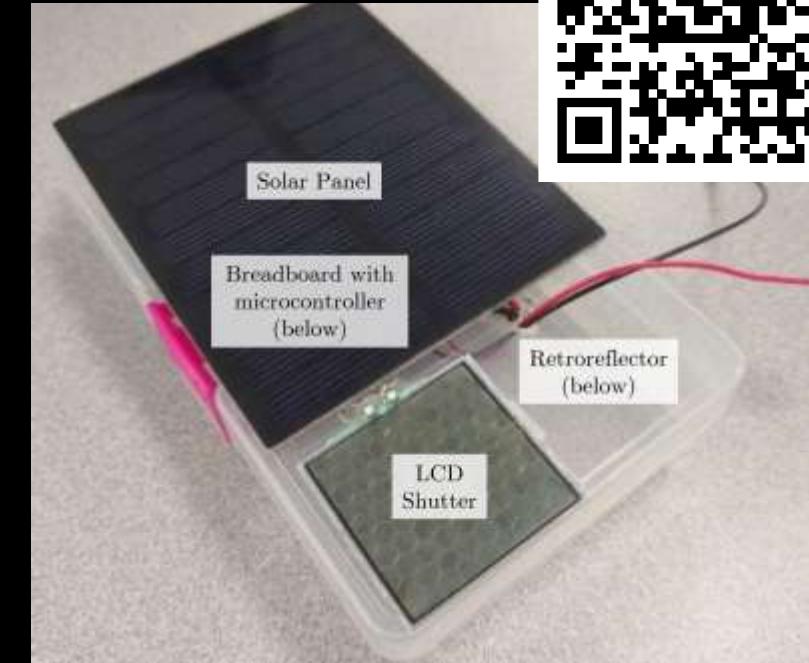
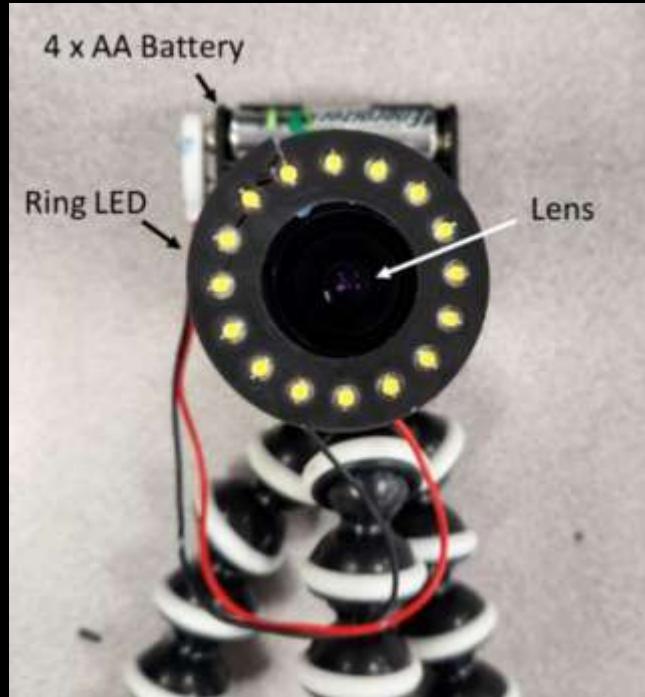
Inventory Tracking

- Tested in single 25 x 3 m lane of operating warehouse
- Lane consists of goods of 3 categories:
 - Just-in-time high-value goods
 - Fast-moving consumer goods
 - High-mix palletized returns



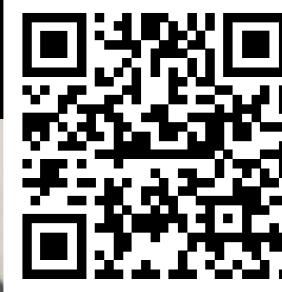
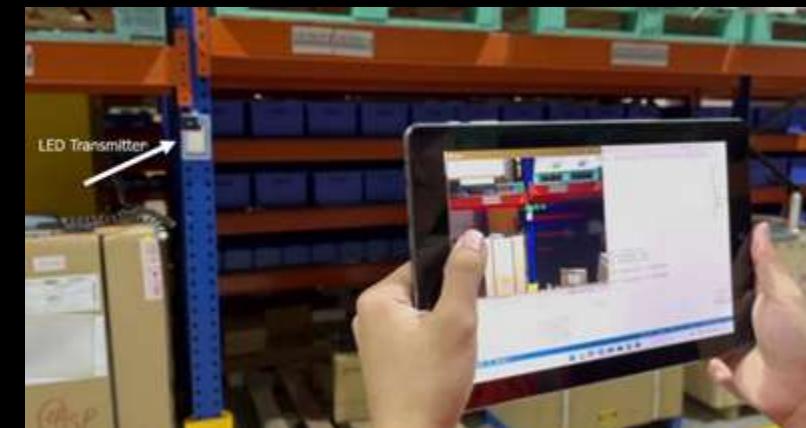
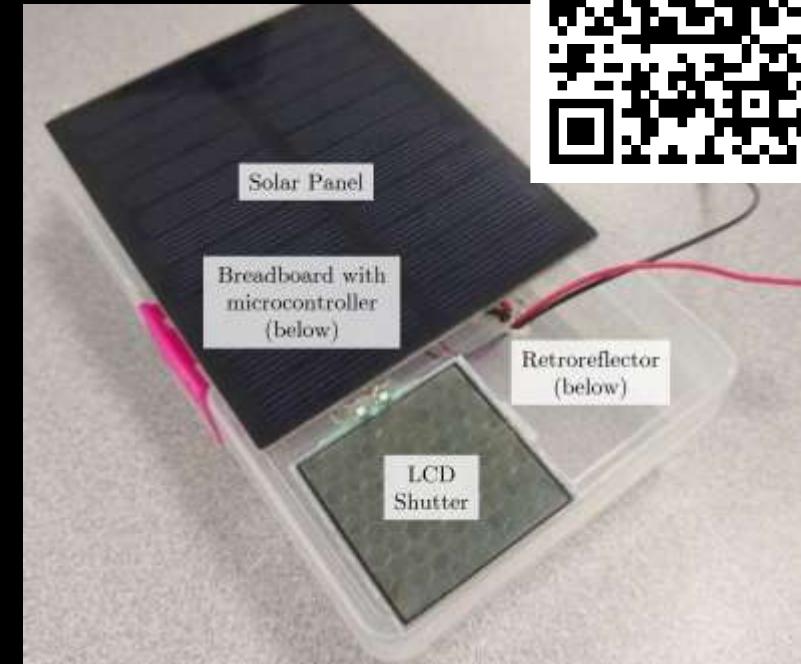
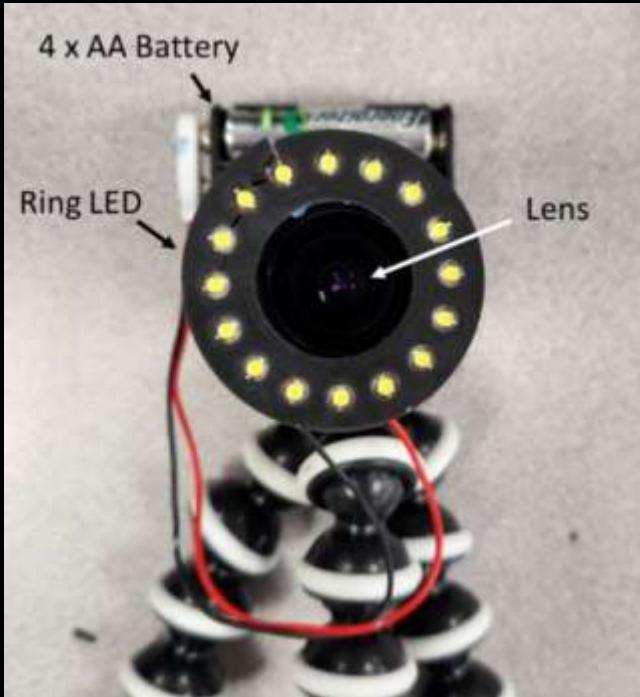
Inventory Tracking

- Passive asset tags attached to inventory broadcasting their ID and metadata
- Tags powered by interrogation light
 - Ring LED mounted on camera



Inventory Tracking

- Worker uses tablet-linked OCC receiver
- Tablet application overlays seen tag positions in real-time
 - Worker can query for specific item and application will guide worker towards it based on received metadata





Key Findings

Positive Outcomes

- Successful readout from up to 25m away
- Positive feedback from users
 - Intuitive user interface
 - Faster look-up time especially for high-mix inventory

Limitations

- Line-of-sight dependency
 - Signal blocked by occlusion from shelves and other items
- Range and angular dependency
 - Typical LC modulator does not perform well off-axis



Key Findings

- Tag acquisition worked well at lab, but poorly at warehouse
- Determined to be due to ambient lighting flickering at similar rate as tags, interfering with reading
- Use higher data rate, but LC contrast drops, affecting range

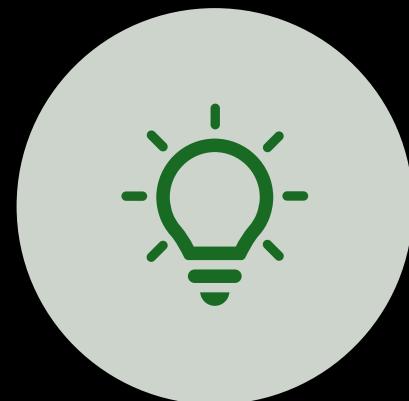
Transmitter	Angle (deg)	Distance (m)	# of Valid Packets	Success Rate (%)
Active LED	0	0.5	44	98.0
	0	1	43	95.6
	0	2	43	95.6
	0	3	44	98.0
	45	1	42	93.3
	45	2	44	98.0
	45	3	42	93.3
	70	1	40	88.9
	70	2	44	98.0
	70	3	44	98.0
	70	4	43	93.3
	70	5	44	98.0
	70	6	44	98.0
	70	8	44	98.0
	70	9	41	91.1
	70	9.5	45	100.0
Passive LCD	0	0.5	40	89.9
	0	1	7	15.6
	0	2	0	0.0
	45	0.5	0	0.0
	70	0.5	0	0.0

At warehouse

Transmitter	Angle (deg)	Distance (m)	# of Valid Packets	Success Rate (%)
Active LED	0	0.5	45	100.0
	0	1	45	100.0
	0	5	45	100.0
	0	10	45	100.0
	45	1	45	100.0
	45	5	45	100.0
	45	10	45	100.0
	70	1	45	100.0
	70	5	45	100.0
	70	10	45	100.0
Passive LCD	0	0.5	45	100.0
	0	1	45	100.0
	0	2	45	100.0
	0	3	45	100.0
	0	4	36	80.0
	0	5	12	26.7
	0	6	0	0.0
	45	0.5	45	100.0
	45	1	40	88.9
	45	2	13	28.8
	45	3	0	0.0
	70	0.5	45	100.0
	70	1	8	17.8
	70	2	1	2.2

At lab

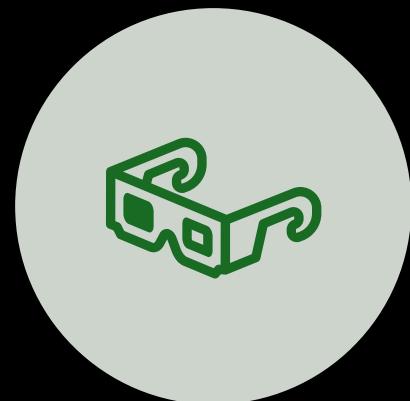
Future Work



Improved tag design
(better modulator,
modulation scheme)



Hybrid OCC + RF system to
overcome line-of-sight issue



Integration with AR glasses
for hands-free use



Conclusion

1. SPAD-based OCC demonstrated promising performance for real-time warehouse tracking
2. Real user validation from warehouse workers in scaled-down real-world testing
3. Remaining hurdles to overcome:
 - Sensitivity to environmental lighting
 - Occlusion/requirement for line-of-sight
 - Ergonomics and better user experience
4. With further refinements, hybrid OCC can transform logistic automation



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for collaborating with us for this work



Q&A



Performance Comparison

(Inventory Tracking)

Technology	GNSS-based	RFID-based	1D/2D Barcode	Optical-based	Our Work
Range	Radio range	2m-200m	1m	20m	10m-1km
Line-of-Sight Required	N	N	Y	Y	Y
Data Rate	Radio speed	<27Mbps	~1200fps	10Mbps	10-100Mbps
Accuracy (Outdoors)	3m to 10m	~10m	N/A	N/A	<5cm to 10m
Accuracy (Indoors)	N/A	~2m	N/A	N/A	<5cm to 10m
Cost Per Tag	~US\$100	~US\$0.005	~US\$0.001	<US\$3	<US\$5
Tag Power	Wired	Passive/Batt	Passive	Wired	Passive/Batt



Performance Comparison

(General Communications)

	Optical					RF			
	HP-OCC	OCC	Optical RIS ^{*1}	Angle Diversity	Vanilla LiFi	T-Wave	mmWave	RIS ^{*1}	
Typical User Data Rate	Medium	Very Low	Very High	Very High	High	Very High	High	High	
Range ^{*2}	Medium LoS Narrow-only	Medium LoS Narrow-only	Medium NLoS ^{*N} Short NLoS ^{*D}	Medium LoS ^{*N} Medium NLoS ^{*D}	Short LoS Narrow-only	Short LoS	Medium LoS	Medium NLoS	
Mobility	Walking	Stationary	Slow Vehicle	Walking	Walking	Slow Vehicle	Slow Vehicle	Slow Vehicle	
Number of Targets	Very High	Very High	Low	Single	Single	High	High	Low	
RX Power Consumption	Medium	High	Very High	Low	Low	High	High	High	
Complexity	Medium	Very Low	High	Low	Low	Very High	High	High	

^{*1} Re-configurable Intelligent Surface

^{*2} LoS and NLoS stand for line-of-sight and non-line-of-sight respectively

^{*N} Narrow beam.

^{*D} Diffused beam.