Combined Radar and Optical Flow Navigation for Flying Robots in Urban Areas

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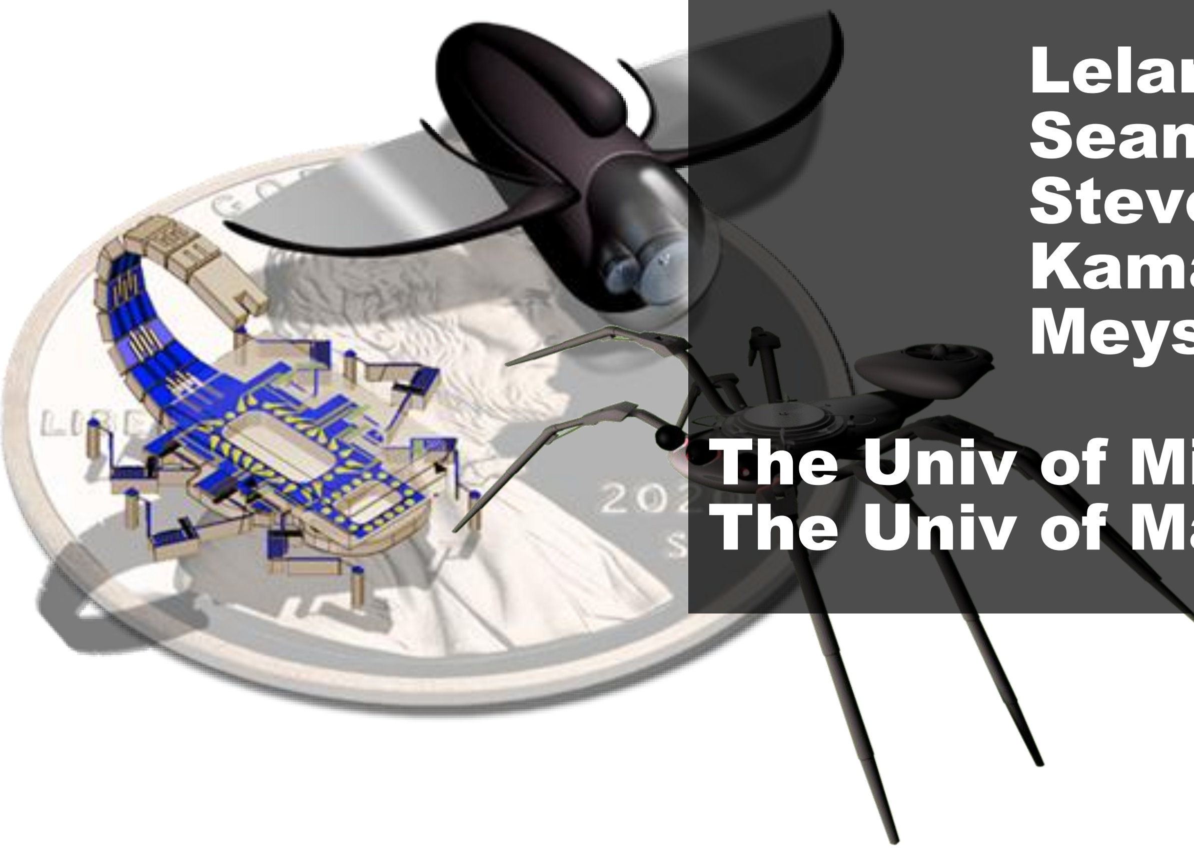


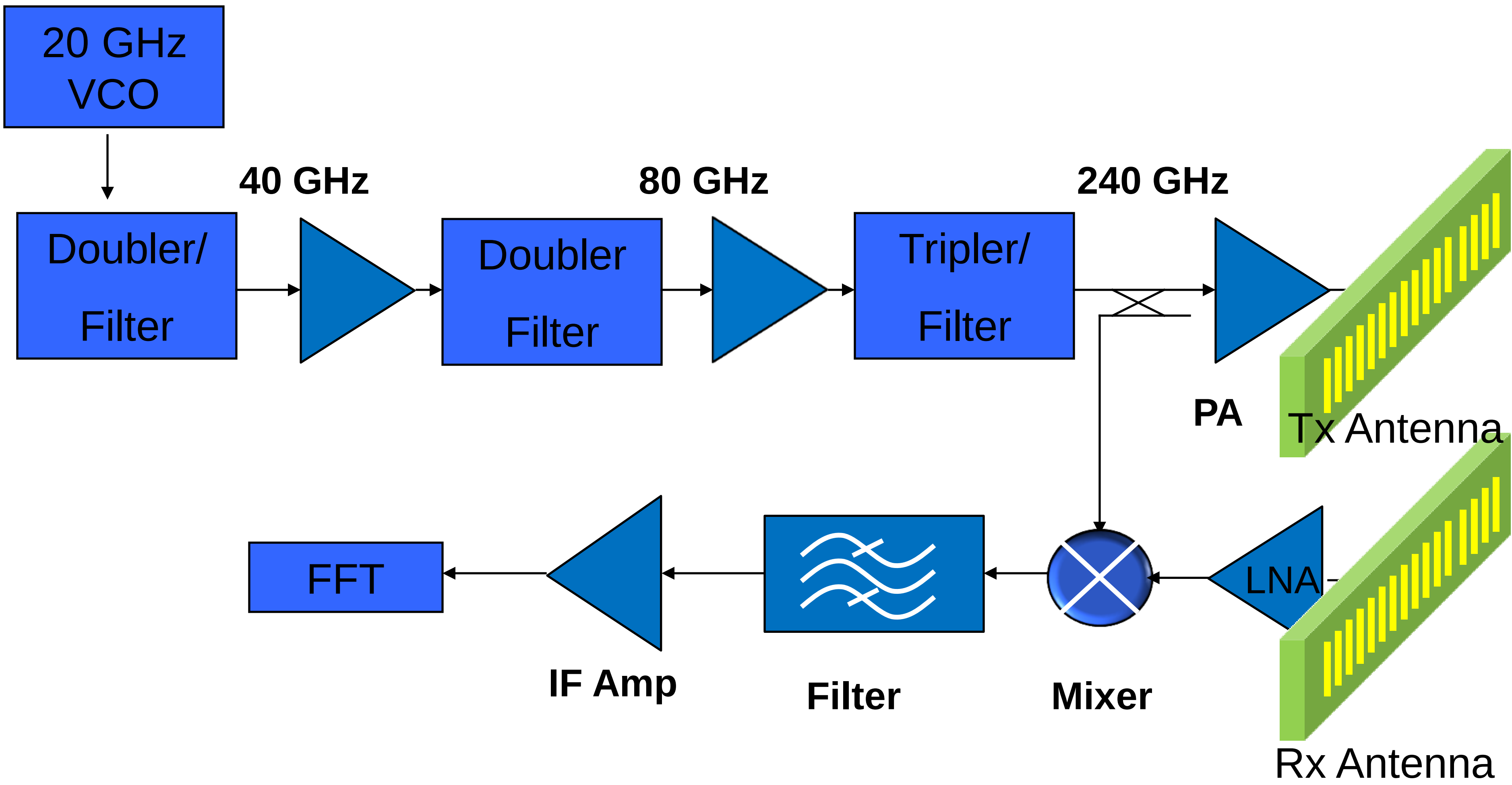
Overview

- **The scenario:** How to autonomously navigate a flying robot in an outdoor urban area, exploring the area without crashing.
- **The issues:**
  – Low power, size, weight
  – Inertial hardware too inaccurate, slow
  – Optical stereo too short-range

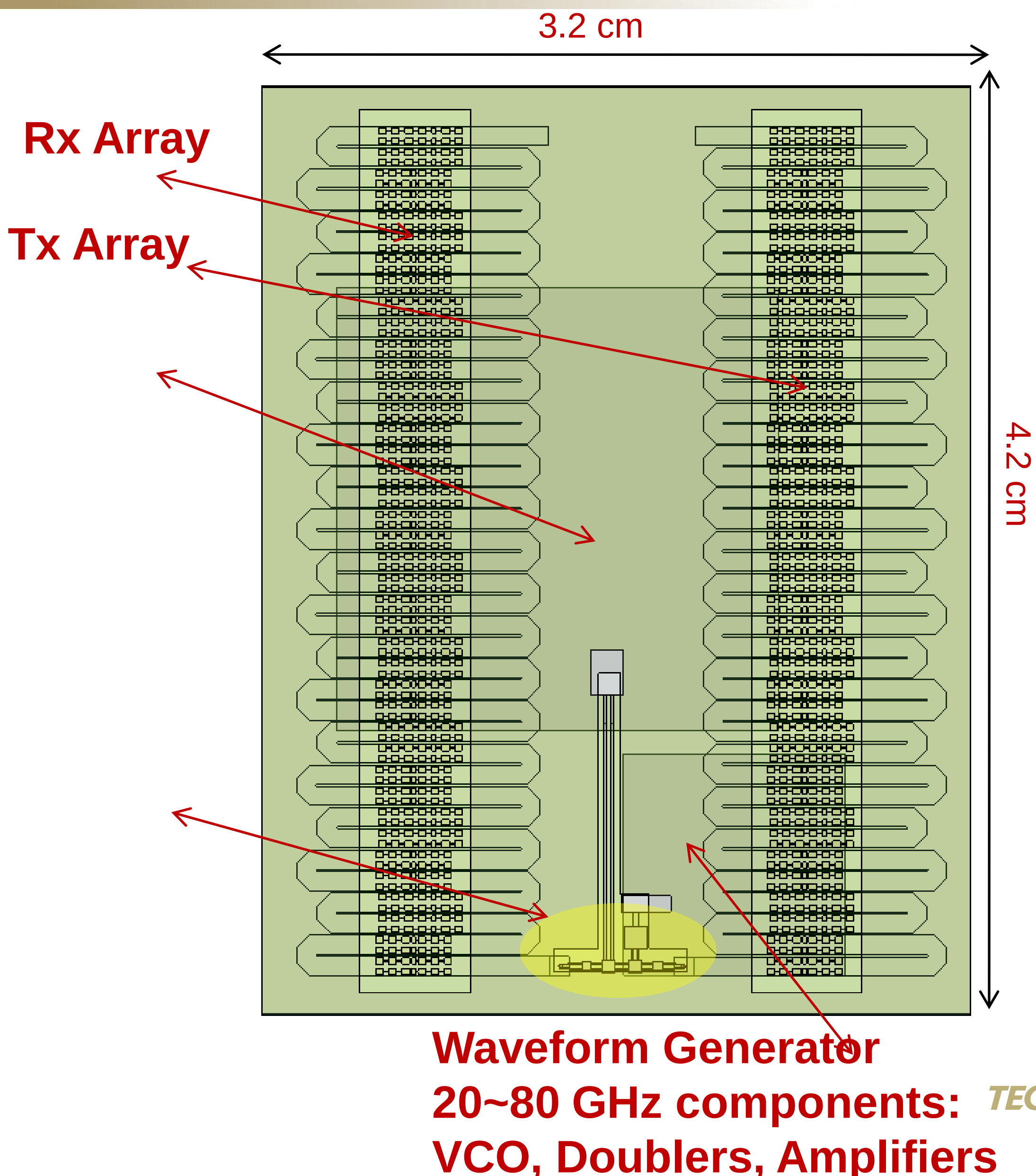
Overview

- **The proposed solution:**
  - – Use optical flow to get inertial information.
  - – Calibrate optical flow with radar.
- **The research:**
  - – Simulate a new radar that is being custom built for this purpose. (Michigan team)
  - – Combine with optical-flow based navigation simulator to verify feasibility (Maryland team)

Proposed Radar Design



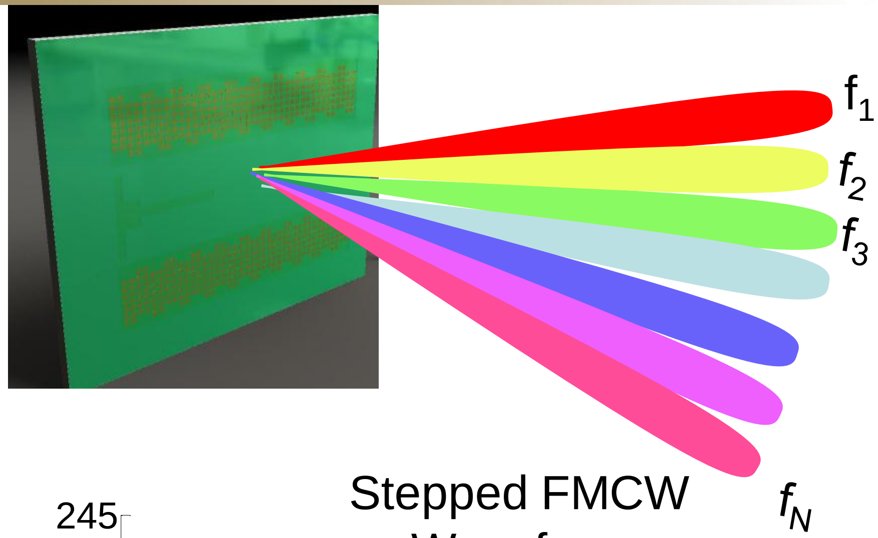
Proposed Radar Design

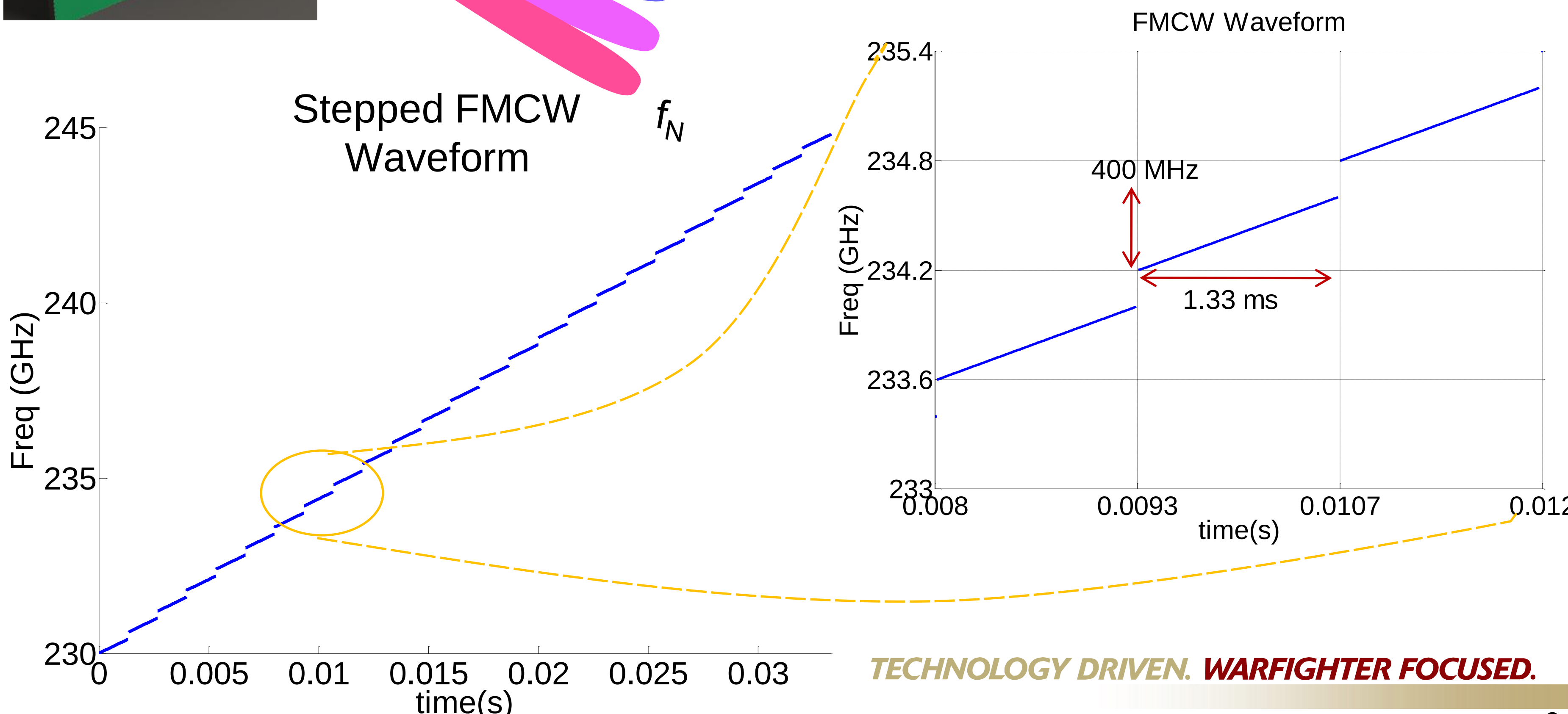


Wavelength	1.2 mm
Peak Tx power	5 dBm
Rx Sensitivity with 5 dB SNR	-135 dBm
Beamwidth	Az: 2^0 El: 8^0
Antenna gain	32 dB
Polarization	Vertical
Volume	2 cm^3
Weight	5 g
Waveform	Stepped FMCW
Field of View	±25deg
Frame update	33 ms
Alias-free range	400m
Range resolution	37.5 cm

Radar Waveform: Stepped FMCW Signal

Beam steering based on frequency scanning





Size, Weight, and Power Budget

Alias-free range 400m, range resolution 0.375m, 16 bit A/D

	Power	Weight	Dimensions
VCO	10mW	4.6mg	4 (mm^2)
Multiplier chain	80mW	0.5g	1cm$\times$1cm
240 GHz Amplifier	50mW	0.1g	
Antennas/frame	0	3.9g	4.2$\times$3.2$\times$0.15 cm^3
LNA+Mixer	50mW	0.2g	
IF Amplifier	10mW	0.1g	
Processor	250mW	0.2g	22 $\times$0.025 cm^3
Total	200mW	5g	4.2$\times$3.2$\times$0.15=2 cm^3

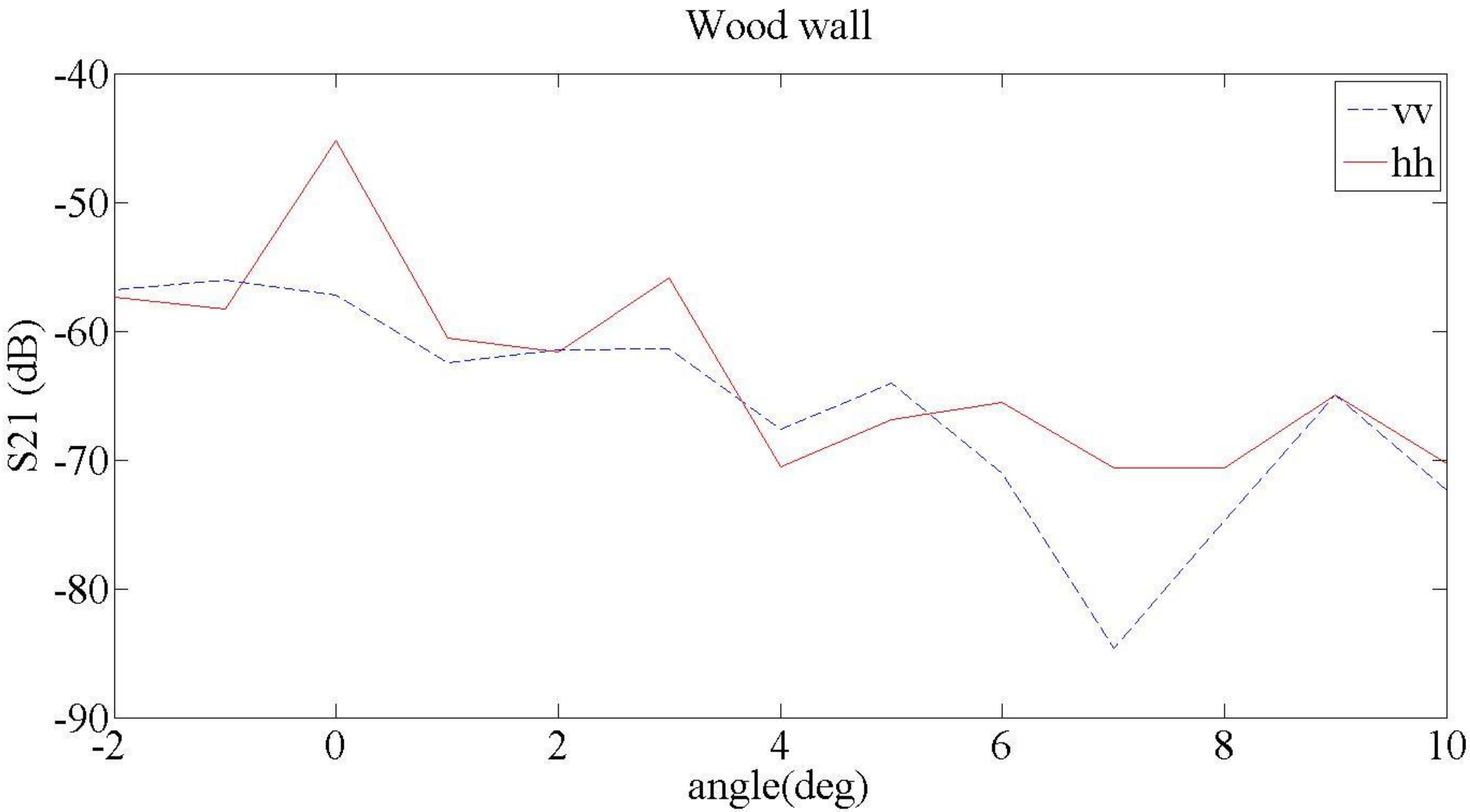
30 frames/sec (continuous operation): 200mw

1 frame/sec (duty cycle 3.33%): **6.7 mW**

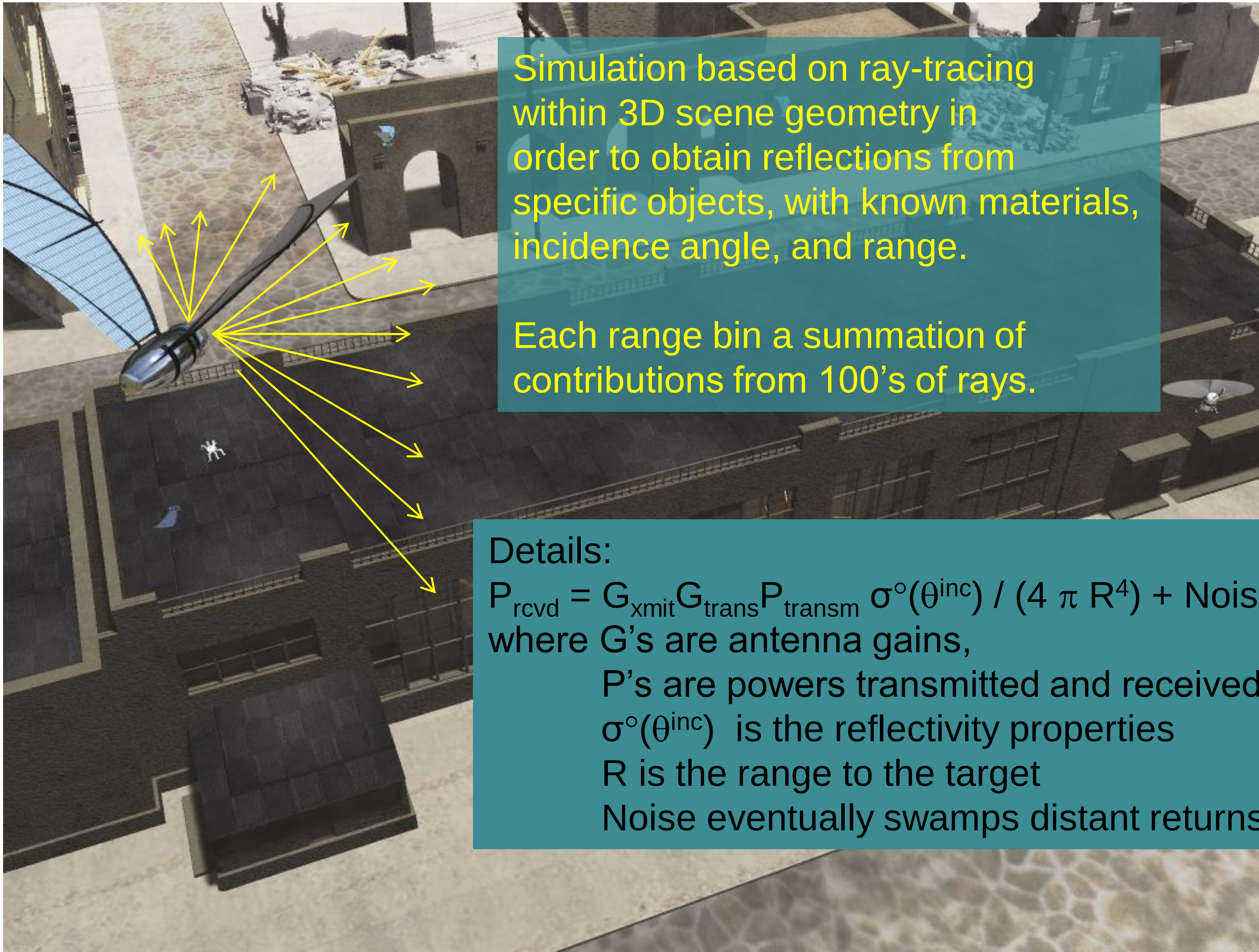
1 frame per 3sec (duty cycle1.1%): **2.22mW**

Radar Measurements

An instrumentation radar operating at 215 GHz was used to measure the reflectivity properties of various targets for inclusion in the simulator's material database.



Radar Simulator Operation



Simulation based on ray-tracing within 3D scene geometry in order to obtain reflections from specific objects, with known materials, incidence angle, and range.

Each range bin a summation of contributions from 100’s of rays.

Details:

$P_{rcvd} = G_{xmit}G_{trans}P_{transm}\ \sigma^{\circ}(\theta^{inc}) / (4\ \pi\ R^4) + Noise_{rcvr}$

where G’s are antenna gains,

P’s are powers transmitted and received.

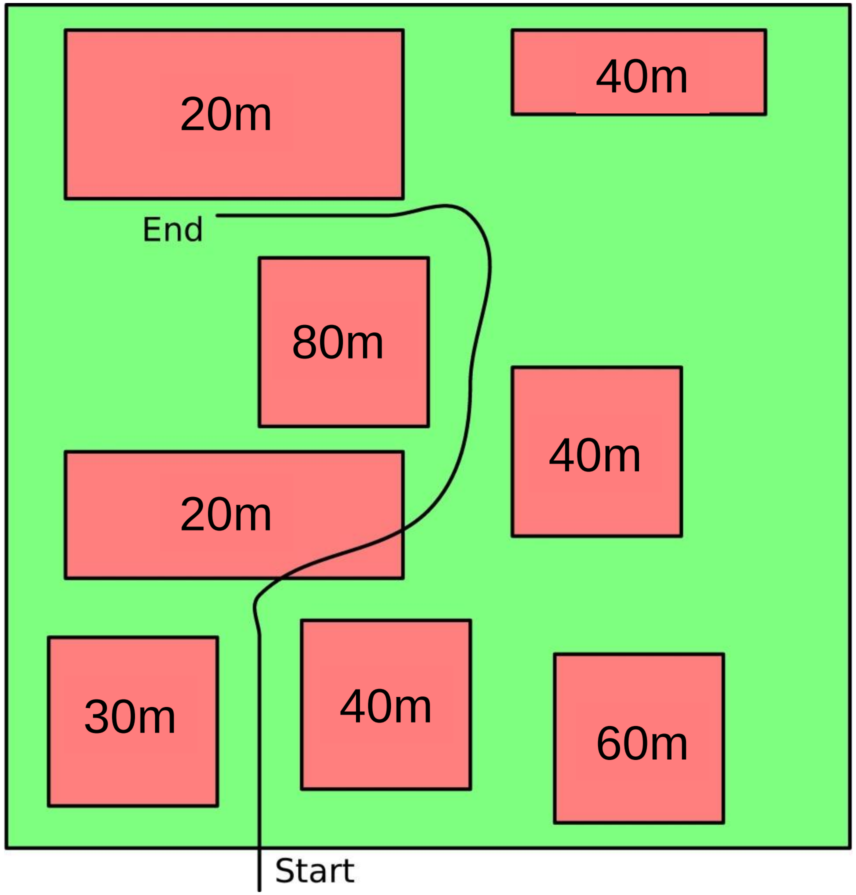
$\sigma^{\circ}(\theta^{inc})$ is the reflectivity properties

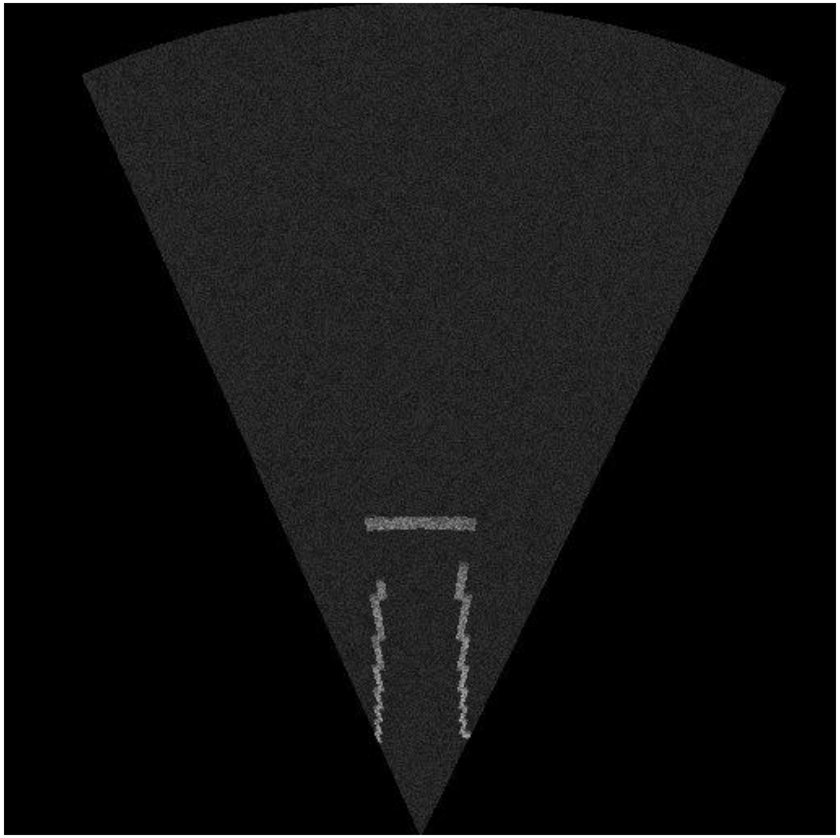
R is the range to the target

Noise eventually swamps distant returns.

Radar/optical-flow Navigation

Example of radar simulation of a flying robot over an urban scene:





Optical Flow Concept

Derivative[Image(θ,ϕ,t)] =

∂ Image / $\partial\theta \cdot \partial\theta$ / ∂t +

∂ Image / $\partial\phi \cdot \partial\phi$ / ∂t +

∂ Image / ∂t $\cong$ 0

- Solve for V_θ, V_ϕ by assuming constant over a few pixels.

Optical Flow Concept

- Can directly obtain angular velocity
- Can also get linear velocity, within a constant.
- If have range to the target for each pixel, can convert to absolute linear velocity.

- Use the radar in order to calibrate the linear velocity measurements.

Optical Flow and Radar Concept

- Both modalities are noisy, so average both over a $15^{o} \times 15^{o}$ region.
- Field-of-view is assumed to cover the entire lower hemisphere.
- Use 100 points equally spaced in this hemisphere.
- Current radar design does not provide this geometry in a single frame, but could be used to estimate it as the robot flies.
- Moving-window average for 0.05 sec: 20 frames/sec

Radar/optical-flow navigation

- Created a 3D model of an area in Fort Benning with lots of buildings.

- Intent was to explore the area:
  - stay away from building walls
  - forward velocity of 1m/sec
  - keep altitude of about 1 meter
  - no path specified

- Simulated vehicle was a quad-rotor.
- Controller was able to vary throttle and pitch.

Radar/optical-flow navigation

Successfully combined optical flow/radar navigation over a simulated Fort Benning scene:

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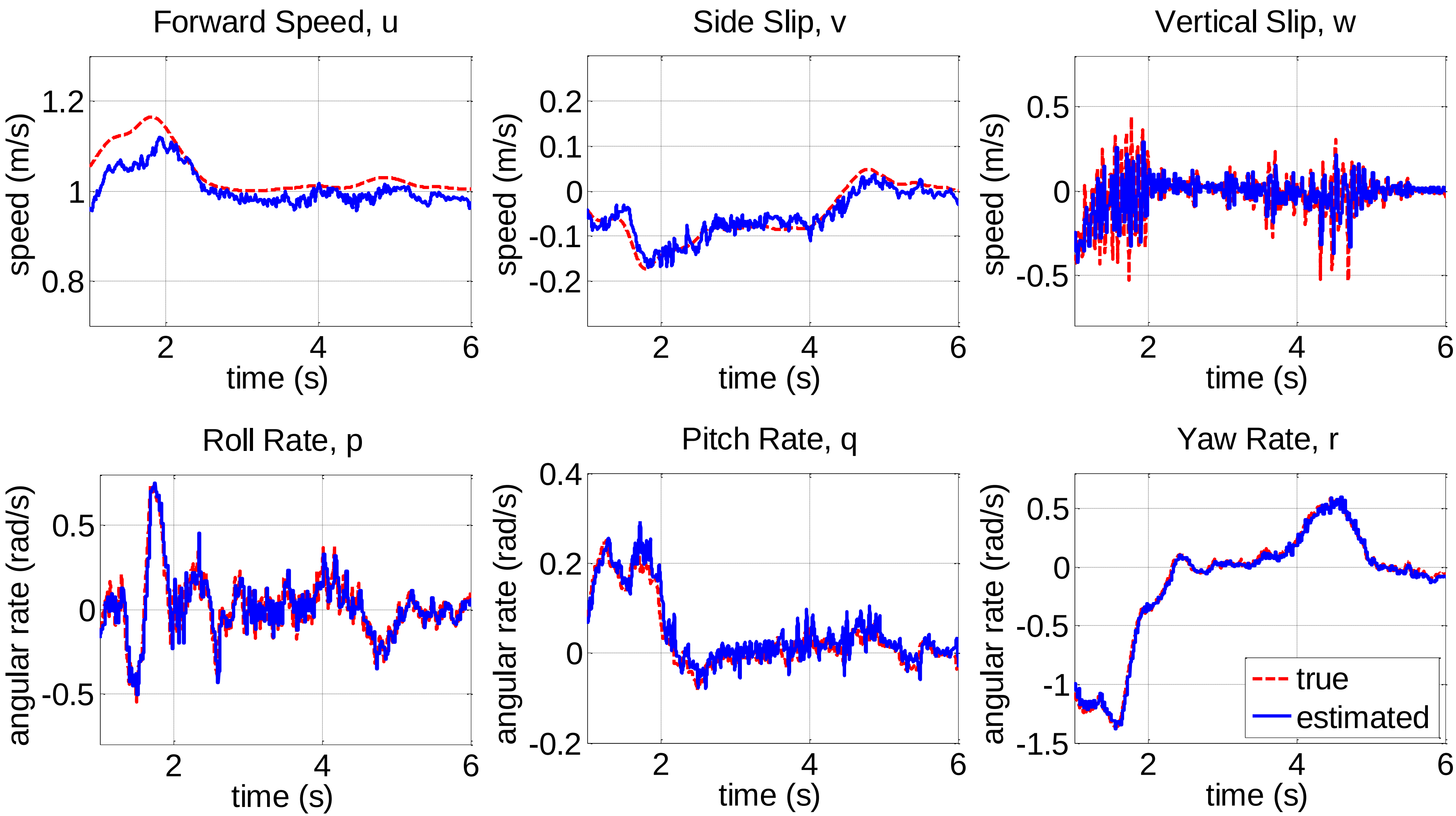
Simulation Results

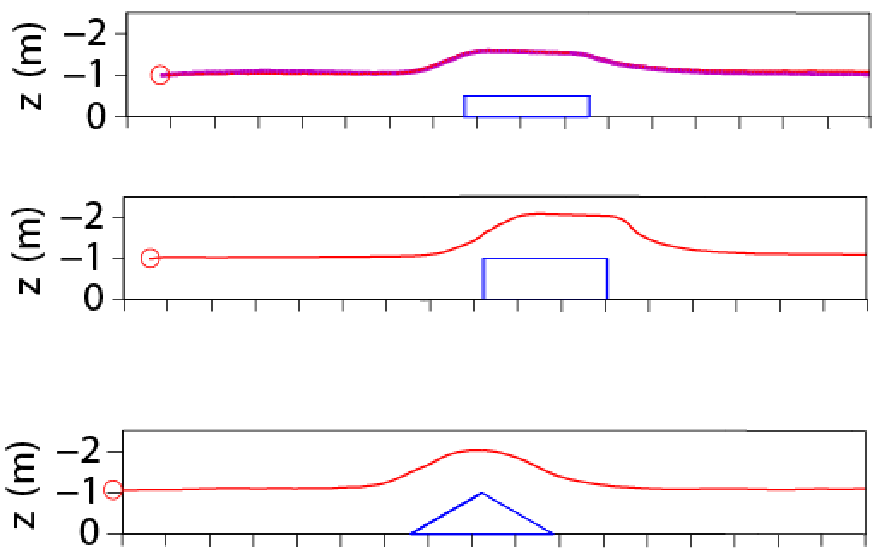


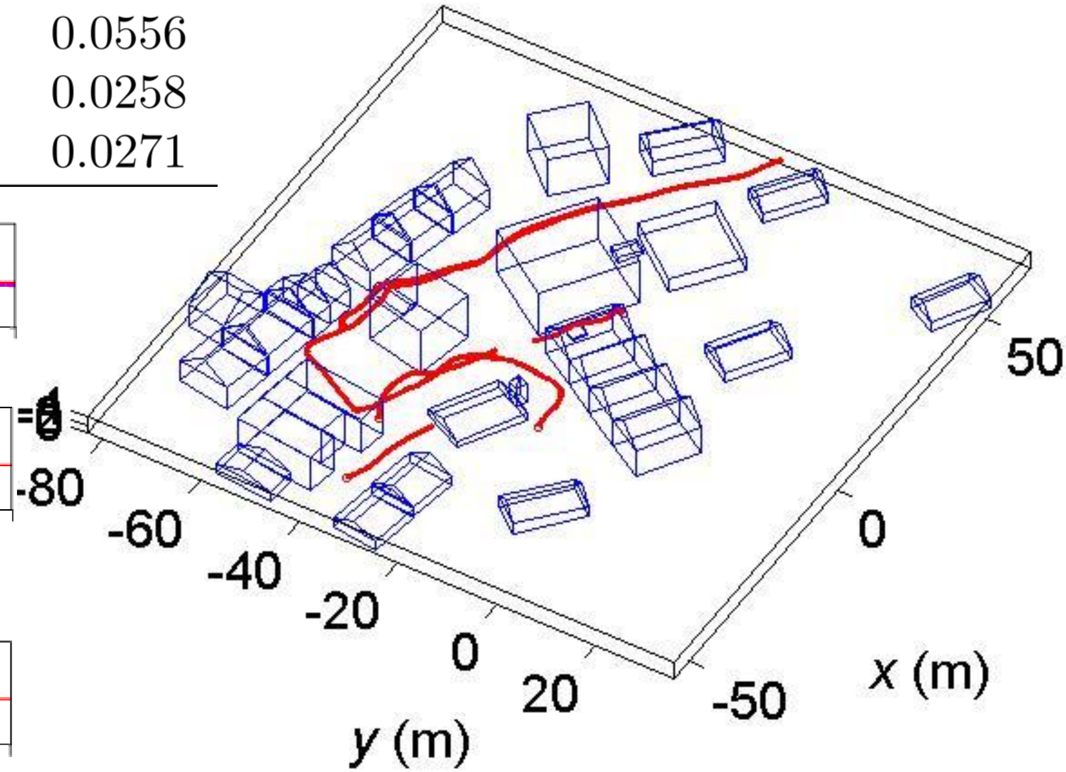
TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Simulation Results

RMS error for estimated states

State	Run 1	Run 2	Run 3	Run 4
u (m/s)	0.0787	0.0413	0.0687	0.0301
v (m/s)	0.0225	0.0151	0.0096	0.0157
w (m/s)	0.1662	0.0926	0.0896	0.0998
p (rad/s)	0.0812	0.0955	0.0671	0.0556
q (rad/s)	0.0425	0.029	0.0295	0.0258
r (rad/s)	0.0379	0.0336	0.0372	0.0271





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Conclusions and Future Work

- Simulations showed successful autonomous navigation in a simulated urban environment:
  - Worst-case velocity error: 7cm/sec
  - Worst-case angular error: 5^{o}/sec
- This, despite noisy measurements and 30cm radar range resolution.

- Would like to improve this so that the radar model is more realistic:
  - forward-looking, not hemispherical
- Increase forward velocity to about 10m/sec
- Radar-only navigation

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