U.S. ARMY TANK AUTOMOTIVE RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

Intelligent Mobility Modeling and Simulation

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Contents

1. Mobility - Autonomy - Latency Relationship

Problem Statement

- Trade space study of Mobility vs. Autonomy vs. Latency

What is the Relation between:

'Design' Variables:
- Delays
- Communication
- Hardware
- Human
- Autonomy

Objective:
- Mobility
- Cost
- Power
- Weight
- Reliability

- Identify means of enhancing mobility

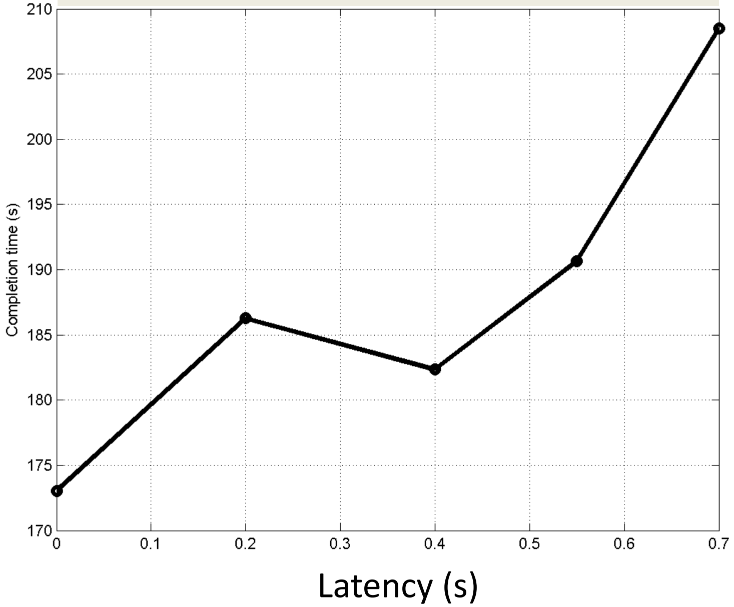
Data Sources

Degree of Autonomy	Teleop	Autonomous
Data Source	Kiosk	Analytical Simulation
Vehicle	Talon	HMMWV
Max Speed	5 mph	67 mph
Path Length	300 m	500 m
Latency	0 - 700 ms	0 - 2000 ms
Source of Latency	Composite (mostly camera sensor)	Sensor and Controller

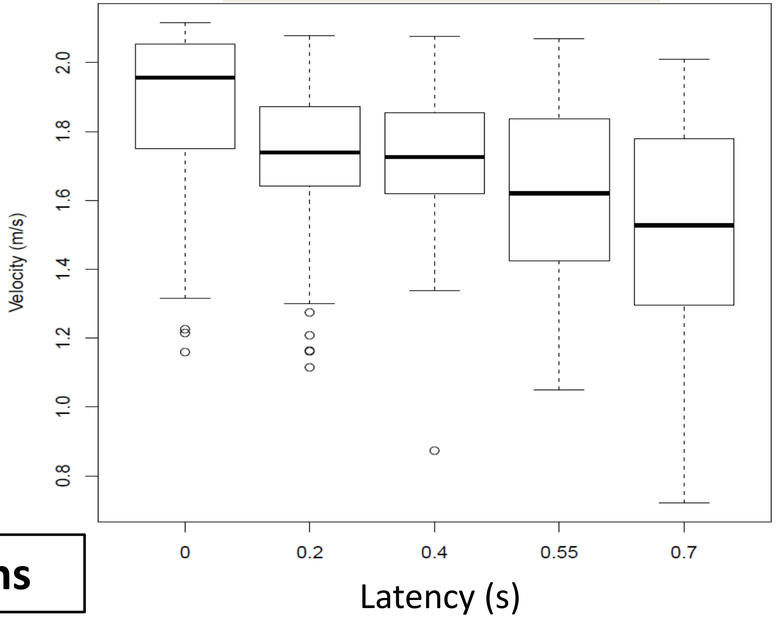
CERDEC can provide realistic values

Teleop Performance of Path Following @ < 5 mph

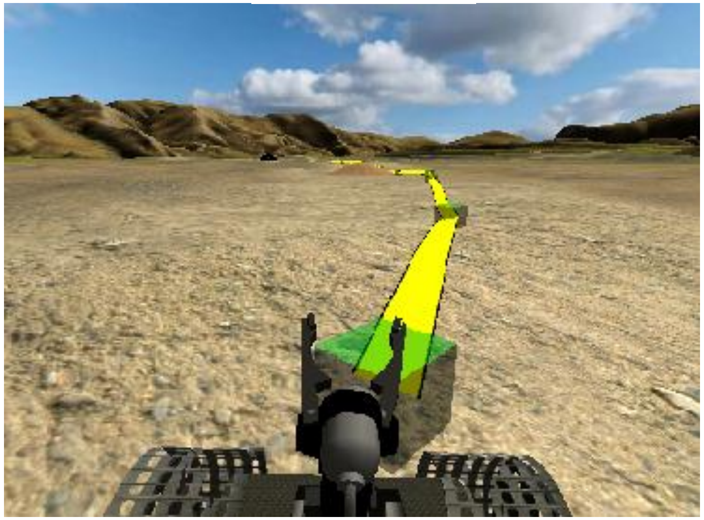
Completion Time vs. Latency



Speed vs. Latency

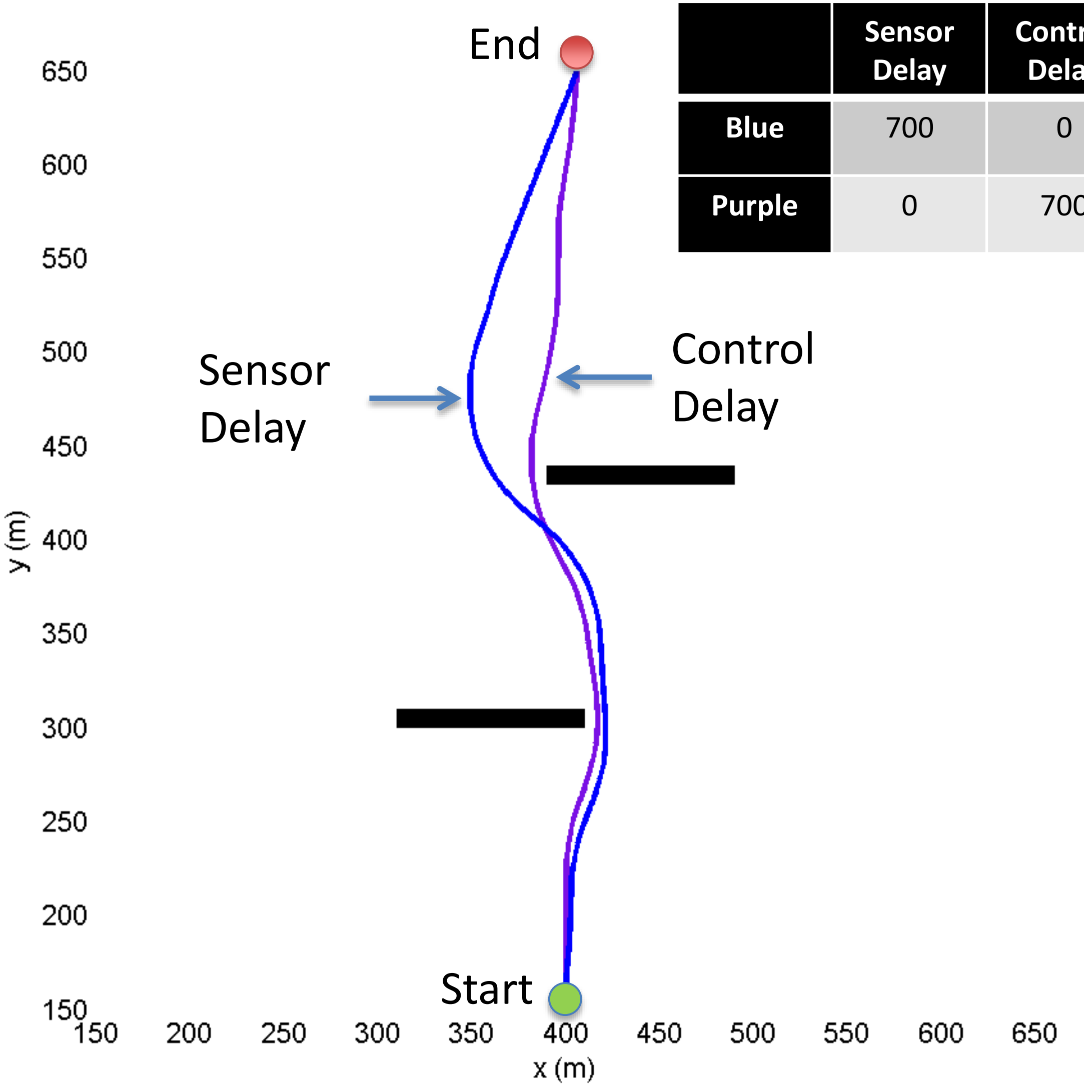


178 Runs



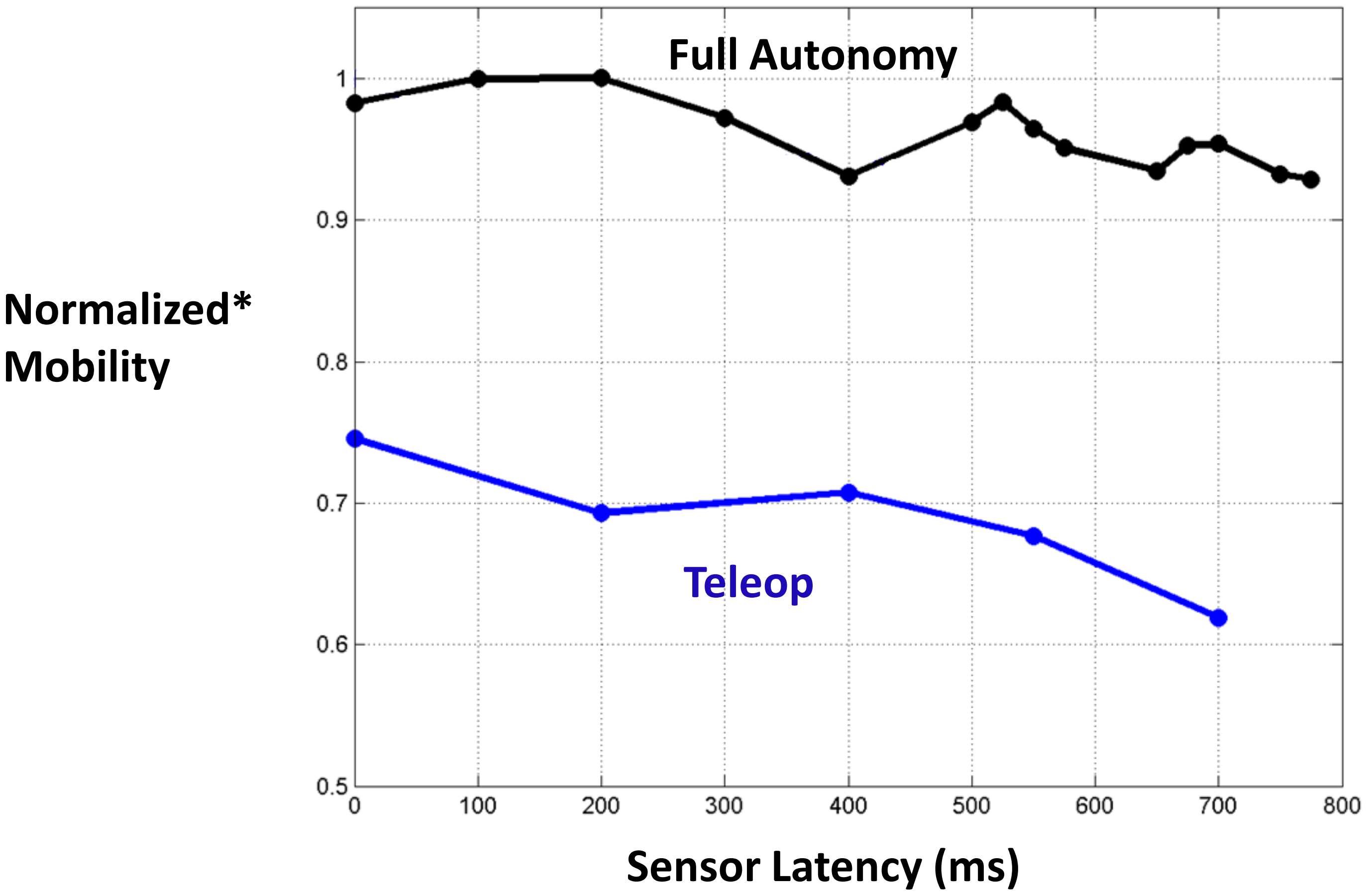
Full Autonomy Performance of Obstacle Avoidance @ 45 mph

- Full autonomy
- Obstacle avoidance
- High speed (45 mph)
- Maintain vehicle stability
- Navigate to minimum time
- Simulation based
- 400 runs



	Sensor Delay	Control Delay
Blue	700	0
Purple	0	700

Mobility vs. Autonomy vs. Latency Comparison



*Normalized Mobility = Minimum Possible Time / Actual Completion Time

Effect of Latency and Vehicle Speed on Fully Autonomous Mobility

15 m/s

Control Delay

Sensor Delay

	0	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
0	🟩 33.85	🟩 33.89	🟩 33.97	🟩 34.08	🟩 34.24	🟩 34.67	🟩 35.00	🟩 35.30	🟩 40.15	🟩 40.64	🟩 40.79	🟩 41.16	🟩 41.62	🟩 42.09	🟩 42.33	🟩 43.03	🟩 43.42	🟩 44.22	🟩 45.03	🟩 45.29	🟩 45.16
100	🟩 33.97	🟩 34.01	🟩 34.10	🟩 34.41	🟩 34.61	🟩 34.88	🟩 35.31	🟩 35.59	🟩 35.50	🟩 41.02	🟩 41.22	🟩 41.45	🟩 43.64	🟩 43.47	🟩 43.83	🟩 44.09	🟩 44.81	🟩 45.07	🟩 47.38	🟩 46.02	🟩 45.68
200	🟩 34.10	🟩 34.37	🟩 34.49	🟩 34.67	🟩 34.95	🟩 35.35	🟩 35.27	🟩 40.54	🟩 40.90	🟩 41.30	🟩 42.02	🟩 46.54	🟩 43.00	🟩 43.93	🟩 44.54	🟩 44.85	🟩 45.04	🟩 44.92	🟩 46.02	🟩 45.99	🟩 45.33
300	🟩 34.16	🟩 34.46	🟩 34.65	🟩 34.91	🟩 39.80	🟩 36.64	🟩 40.54	🟩 41.29	🟩 42.01	🟩 42.14	🟩 43.12	🟩 43.50	🟩 43.87	🟩 44.18	🟩 44.31	🟩 44.72	🟩 44.96	🟩 45.61	🟩 46.65	🟩 46.27	🟩 46.07
400	🟩 34.61	🟩 34.77	🟩 35.39	🟩 35.93	🟩 40.74	🟩 36.34	🟩 41.55	🟩 41.98	🟩 42.08	🟩 43.15	🟩 43.38	🟩 43.60	🟩 44.13	🟩 44.69	🟩 44.73	🟩 45.84	🟩 45.76	🟩 47.16	🟩 46.48	🟩 46.10	20.77
500	🟩 35.20	🟩 35.56	🟩 36.01	🟩 40.66	🟩 41.21	🟩 41.82	🟩 41.75	🟩 42.02	🟩 42.46	🟩 43.43	🟩 43.54	🟩 43.68	🟩 44.22	🟩 45.98	🟩 49.61	🟩 46.06	🟩 46.45	20.53	20.77	20.10	20.77
600	🟩 39.52	🟩 39.85	🟩 36.17	🟩 40.92	🟩 41.37	🟩 41.90	🟩 41.71	🟩 42.76	🟩 42.67	🟩 43.08	🟩 42.36	🟩 43.82	🟩 44.73	🟩 45.01	🟩 45.46	🟩 43.59	20.77	10.05	10.05	10.05	10.05
700	🟩 39.96	🟩 40.29	🟩 41.02	🟩 41.22	🟩 41.31	🟩 41.88	🟩 42.91	🟩 42.92	🟩 43.40	🟩 43.83	🟩 45.01	🟩 43.20	🟩 45.13	🟩 45.80	🟩 45.33	20.77	20.77	10.05	10.05	10.05	10.05
800	🟩 40.35	🟩 40.98	🟩 41.26	🟩 41.69	🟩 42.29	🟩 43.03	🟩 42.93	🟩 43.52	🟩 43.34	🟩 44.22	🟩 44.80	🟩 45.32	🟩 44.86	🟩 45.64	20.77	20.77	21.44	10.05	10.05	10.05	10.05
900	🟩 41.06	🟩 41.41	🟩 41.70	🟩 42.18	🟩 42.71	🟩 43.32	🟩 43.55	🟩 43.60	🟩 43.95	🟩 44.30	🟩 45.09	🟩 45.49	20.77	20.77	20.77	20.77	21.44	10.05	10.05	10.05	10.05
1000	🟩 41.31	🟩 41.70	🟩 41.98	🟩 43.07	🟩 0.00	🟩 43.32	🟩 43.56	🟩 44.18	🟩 45.59	🟩 45.08	🟩 46.08	20.77	20.10	20.10	20.77	21.44	10.05	10.05	10.05	10.05	10.05
1100	🟩 41.74	🟩 40.51	🟩 42.20	🟩 43.34	🟩 43.39	🟩 43.83	🟩 44.34	🟩 45.29	🟩 45.92	🟩 45.14	20.74	20.10	20.10	20.77	20.77	22.11	10.05	10.05	10.05	10.05	10.05
1200	🟩 41.92	🟩 42.26	🟩 43.28	🟩 43.08	🟩 44.15	🟩 44.51	🟩 45.65	🟩 45.83	🟩 44.92	20.70	20.10	20.10	20.77	20.77	21.44	22.11	10.05	10.05	10.05	10.05	10.05
1300	🟩 42.52	🟩 42.61	🟩 43.11	🟩 43.54	🟩 43.78	🟩 44.76	🟩 44.96	20.77	20.77	20.77	21.44	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05
1400	🟩 43.20	🟩 43.11	🟩 43.46	🟩 43.99	🟩 44.54	🟩 44.92	20.77	20.77	20.77	20.77	21.44	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05
1500	🟩 43.22	🟩 43.47	🟩 44.03	20.62	20.61	20.77	20.77	20.77	20.77	21.44	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05
1600	🟩 43.79	🟩 44.14	🟩 44.51	20.74	20.77	20.77	20.77	20.77	20.77	22.11	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05
1700	🟩 44.03	🟩 44.46	🟩 44.26	20.77	20.77	20.77	20.77	20.77	20.77	22.11	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05
1800	🟩 44.31	🟩 45.20	20.77	20.77	20.77	20.77	20.77	20.77	21.44	22.11	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05
1900	20.77	20.77	20.77	21.44	20.77	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05
2000	20.77	20.77	20.77	21.44	22.78	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05

FAIL

20 m/s

Control Delay

Sensor Delay

	0	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
0	🟩 25.45	🟩 25.56	🟩 25.80	🟩 26.00	🟩 26.31	🟩 26.58	🟩 27.60	🟩 33.55	🟩 34.05	🟩 33.75	🟩 34.15	🟩 34.51	🟩 33.64	🟩 34.03	🟩 34.38	🟩 33.13	🟩 33.15	🟩 32.93	🟩 29.50	🟩 29.98	7.50
100	🟩 25.74	🟩 25.94	🟩 30.40	🟩 30.83	🟩 31.31	🟩 31.98	🟩 31.71	🟩 31.95	🟩 32.27	🟩 31.93	🟩 32.19	🟩 32.45	🟩 32.63	🟩 31.72	🟩 30.27	🟩 31.28	7.50	7.50	7.50	7.50	7.50
200	🟩 29.99	🟩 30.34	🟩 30.76	🟩 33.61	🟩 31.27	🟩 33.12	🟩 32.10	🟩 31.92	🟩 32.83	🟩 32.97	🟩 33.03	🟩 32.07	🟩 32.13	🟩 31.86	🟩 30.59	15.00	7.50	7.50	7.50	7.50	7.50
300	🟩 30.35	🟩 30.70	🟩 30.86	🟩 31.26	🟩 32.77	🟩 33.33	🟩 32.71	🟩 32.84	🟩 33.07	🟩 32.17	🟩 32.34	🟩 32.54	🟩 31.49	🟩 31.34	🟩 28.38	7.50	7.50	7.50	7.50	7.50	7.50
400	🟩 26.87	🟩 31.69	🟩 32.04	🟩 32.29	🟩 32.22	🟩 32.59	🟩 32.92	🟩 33.04	🟩 32.49	🟩 32.69	🟩 32.84	🟩 32.77	🟩 32.61	🟩 30.91	🟩 28.05	7.50	7.50	7.50	7.50	7.50	7.50
500	🟩 31.42	🟩 31.83	🟩 32.21	🟩 32.16	🟩 32.51	🟩 33.18	🟩 32.54	🟩 32.69	🟩 32.96	🟩 33.54	15.50	15.50	🟩 32.66	🟩 30.45	🟩 29.30	7.50	7.50	7.50	7.50	7.50	7.50
600	🟩 30.93	🟩 30.78	🟩 31.12	🟩 31.57	🟩 32.18	🟩 32.39	🟩 32.18	🟩 32.96	🟩 31.97	🟩 28.64	🟩 31.67	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50
700	🟩 31.39	🟩 31.60	🟩 31.86	🟩 31.46	🟩 31.68	🟩 31.84	🟩 32.37	🟩 32.25	🟩 32.04	🟩 29.47	15.00	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50
800	🟩 31.49	🟩 31.92	🟩 31.43	🟩 31.11	🟩 32.18	🟩 32.42	🟩 32.52	🟩 31.79	🟩 32.08	15.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50
900	🟩 31.22	🟩 31.61	🟩 31.91	🟩 32.91	🟩 32.52	15.50	15.50	15.50	15.50	16.00	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50
1000	🟩 31.70	🟩 32.58	15.50	🟩 33.21	15.50	15.50	15.50	15.50	15.50	15.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50
1100	🟩 31.60	🟩 31.61	🟩 31.91	🟩 32.13	15.50	15.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50
1200	🟩 31.66	🟩 31.82	15.50	15.50	15.50	15.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50
1300	🟩 31.73	15.50	15.50	15.50	15.50	15.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50
1400	15.50	15.50	15.50	15.50	16.00	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50
1500	15.50	15.50	15.50	15.50	15.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50
1600	15.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50
1700	15.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50
1800	15.00	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50
1900	16.00	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50
2000	16.00	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50

FAIL

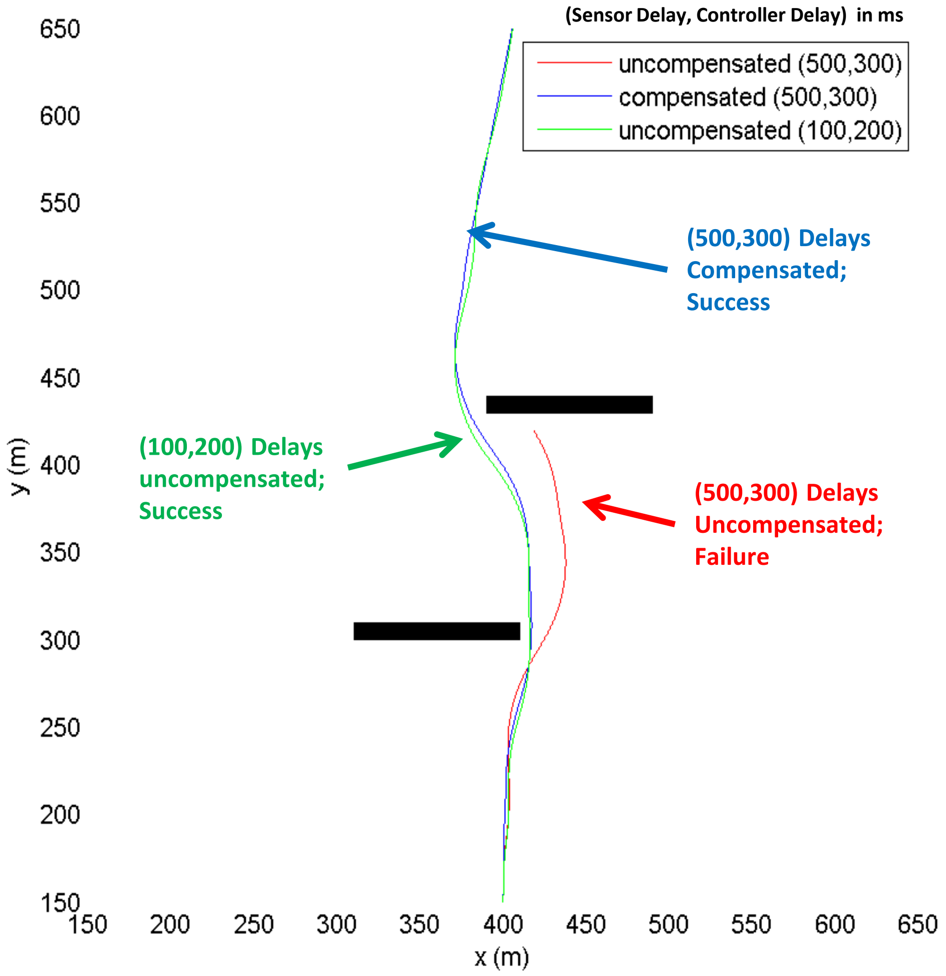
100m Lidar Range, 10m update spacing

- Green = successful run with numerical value indicating travel time
- Symmetric pattern of results indicates that combined latency value is relevant parameter
- Increased vehicle speed results in decreased region of success

Latency Compensation to Improve Fully Autonomous Mobility

- Latency can be compensated for within the algorithm

- Compensated latent system recovers majority of the performance of a zero-latency system



(Sensor Delay, Controller Delay) in ms

(500,300) Delays Compensated; Success

(100,200) Delays uncompensated; Success

(500,300) Delays Uncompensated; Failure

Effect of Latency Compensation on Fully Autonomous Mobility

Without Delay Compensation

Control Delay

Sensor Delay

	0	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
0	33.85	33.89	33.97	34.08	34.24	34.67	35.00	35.30	40.15	40.64	40.79	41.16	41.62	42.09	42.33	43.03	43.42	44.22	45.03	45.29	45.16
100	33.97	34.01	34.10	34.41	34.61	34.88	35.31	35.59	35.50	41.02	41.22	41.45	43.64	43.47	43.83	44.09	44.81	45.07	47.38	46.02	45.68
200	34.10	34.37	34.49	34.67	34.95	35.35	35.27	40.54	40.90	41.30	42.02	46.54	43.00	43.93	44.54	44.85	45.04	44.92	46.02	45.99	45.33
300	34.16	34.46	34.65	34.91	39.80	36.64	40.54	41.29	42.01	42.14	43.12	43.50	43.87	44.18	44.31	44.72	44.96	45.61	46.65	46.27	46.07
400	34.61	34.77	35.39	35.93	40.74	36.34	41.55	41.98	42.08	43.15	43.38	43.60	44.13	44.69	44.73	45.84	45.76	47.16	46.48	46.10	20.77
500	35.20	35.56	36.01	40.66	41.21	41.82	41.75	42.02	42.46	43.43	43.54	43.68	44.22	45.98	49.61	46.06	46.45	20.53	20.77	20.10	20.77
600	39.52	39.85	36.17	40.92	41.37	41.90	41.71	42.76	42.67	43.08	42.36	43.82	44.73	45.01	45.46	43.59	20.77	10.05	10.05	10.05	10.05
700	39.96	40.29	41.02	41.22	41.31	41.88	42.91	42.92	43.40	43.83	45.01	43.20	45.13	45.80	45.33	20.77	20.77	10.05	10.05	10.05	10.05
800	40.35	40.98	41.26	41.69	42.29	43.03	42.93	43.52	43.34	44.22	44.80	45.32	44.86	45.64	20.77	20.77	21.44	10.05	10.05	10.05	10.05
900	41.06	41.41	41.70	42.18	42.71	43.32	43.55	43.60	43.95	44.30	45.09	45.49	20.77	20.77	20.77	20.77	21.44	10.05	10.05	10.05	10.05
1000	41.31	41.70	41.98	43.07	0.00	43.32	43.56	44.18	45.59	45.08	46.08	20.77	20.10	20.10	20.77	21.44	10.05	10.05	10.05	10.05	10.05
1100	41.74	40.51	42.20	43.34	43.39	43.83	44.34	45.29	45.92	45.14	20.74	20.10	20.10	20.77	20.77	22.11	10.05	10.05	10.05	10.05	10.05
1200	41.92	42.26	43.28	43.08	44.15	44.51	45.65	45.83	44.92	20.70	20.10	20.10	20.77	20.77	21.44	22.11	10.05	10.05	10.05	10.05	10.05
1300	42.52	42.61	43.11	43.54	43.78	44.76	44.96	20.77	20.77	20.77	21.44	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05
1400	43.20	43.11	43.46	43.99	44.54	44.92	20.77	20.77	20.77	20.77	21.44	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05
1500	43.22	43.47	44.03	20.62	20.61	20.77	20.77	20.77	20.77	21.44	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05
1600	43.79	44.14	44.51	20.74	20.77	20.77	20.77	20.77	20.77	22.11	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05
1700	44.03	44.46	44.26	20.77	20.77	20.77	20.77	20.77	20.77	22.11	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05
1800	44.31	45.20	20.77	20.77	20.77	20.77	20.77	20.77	21.44	22.11	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05
1900	20.77	20.77	20.77	21.44	20.77	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05
2000	20.77	20.77	20.77	21.44	22.78	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05	10.05

FAIL

With Delay Compensation

Control Delay

Sensor Delay

	0	100	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
0	33.79	33.82	33.63	33.63	33.74	33.81	33.80	34.00	33.94	33.73	33.83	33.93	33.98	34.01	34.12	34.14	34.43	34.04	34.09	34.35	34.35
100	33.79	33.61	33.70	33.83	33.77	33.94	33.80	33.96	33.73	33.79	33.93	33.97	34.13	34.12	34.21	33.76	33.99	34.20	34.06	34.44	34.26
200	33.59	33.80	33.86	33.89	33.91	33.88	33.78	33.67	33.83	33.82	33.97	34.13	34.12	33.85	33.76	34.08	34.22	34.06	34.36	34.33	34.50
300	33.84	33.86	33.86	33.84	33.87	33.85	33.73	33.82	33.91	33.97	34.13	34.23	34.03	33.76	34.03	34.10	34.06	34.16	34.38	34.45	34.84
400	33.77	33.83	33.94	33.89	33.93	33.73	33.73	33.86	33.92	34.08	34.01	34.19	33.76	33.86	34.12	34.23	34.38	34.23	34.58	34.77	35.07
500	34.00	34.02	33.97	33.75	33.73	33.74	33.85	33.95	34.05	34.14	34.17	33.86	33.86	34.12	34.06	34.46	34.26	34.47	34.81	35.02	35.17
600	33.91	33.83	33.75	33.72	33.81	33.93	33.91	34.06	34.16	33.82	34.35	33.93	34.20	34.22	34.34	34.52	34.36	34.68	35.00	35.11	39.68
700	33.81	33.92	33.80	33.79	33.80	33.91	34.03	34.15	34.19	33.85	33.99	34.11	34.29	34.43	34.34	34.53	34.79	35.10	39.49	39.59	39.69
800	33.82	33.86	33.75	33.92	33.98	34.03	34.19	34.27	34.43	34.05	34.16	34.23	34.42	34.36	34.36	34.77	35.00	39.60	39.67	39.55	40.12
900	33.75	33.78	33.87	34.01	34.07	33.99	34.11	34.43	33.86	34.19	34.22	34.32	34.40	34.48	34.75	35.19	35.18	39.56	39.70	40.23	39.75
1000	33.79	33.87	33.88	34.06	34.18	34.17	33.82	33.94	34.05	34.06	34.44	34.37	34.52	34.77	35.09	39.52	39.69	39.67	40.13	39.75	39.77
1100	33.88	34.09	34.13	34.01	34.22	34.56	33.94	34.11	34.23	34.45	34.26	34.52	34.72	35.15	39.35	39.36	39.77	40.26	39.75	39.78	39.95
1200	34.12	34.11	34.19	33.84	34.37	33.86	34.10	34.24	34.37	34.38	34.57	34.71	35.02	39.56	39.58	39.83	40.13	39.87	39.79	39.95	40.02
1300	34.22	34.01	34.19	34.43	33.92	34.10	34.32	34.38	34.33	34.49	34.81	34.99	39.55	39.61	39.68	40.09	39.75	39.85	39.92	39.95	39.99
1400	34.20	33.83	34.41	33.92	34.18	34.23	34.28	34.38	34.60	34.81	35.08	39.34	39.61	39.66	40.08	39.75	39.85	39.84	39.99	39.95	40.07
1500	34.17	34.43	33.94	33.96	34.18	34.36	34.26	34.36	34.68	39.47	39.58	39.56	39.74	40.15	39.75	39.85	39.94	39.98	39.97	40.15	40.26
1600	33.84	38.80	34.14	34.27	34.31	34.45	34.44	34.78	34.95	39.41	39.65	39.73	40.07	39.75	39.85	39.91	39.92	39.99	40.15	40.21	40.01
1700	33.92	34.01	34.17	34.33	34.37	34.49	34.76	39.42	39.54	39.61	39.80	40.12	39.82	39.76	39.95	39.91	40.01	40.07	40.19	40.05	40.01
1800	34.00	34.19	34.39	34.25	34.59	34.82	35.07	39.35	39.64	39.69	40.13	39.75	39.85	39.76	39.94	40.03	40.16	40.26	40.06	40.01	40.12
1900	34.23	34.42	34.52	34.54	34.73	35.14	35.20	39.60	39.72	40.07	39.75	39.83	39.89	39.89	39.99	40.00	40.20	39.94	40.00	40.10	40.13
2000	34.32	34.40	34.60	34.76	35.09	39.33	39.66	39.76	40.04	39.81	39.85	39.89	39.92	40.02	40.11	40.27	40.05	40.05	40.07	40.14	40.27

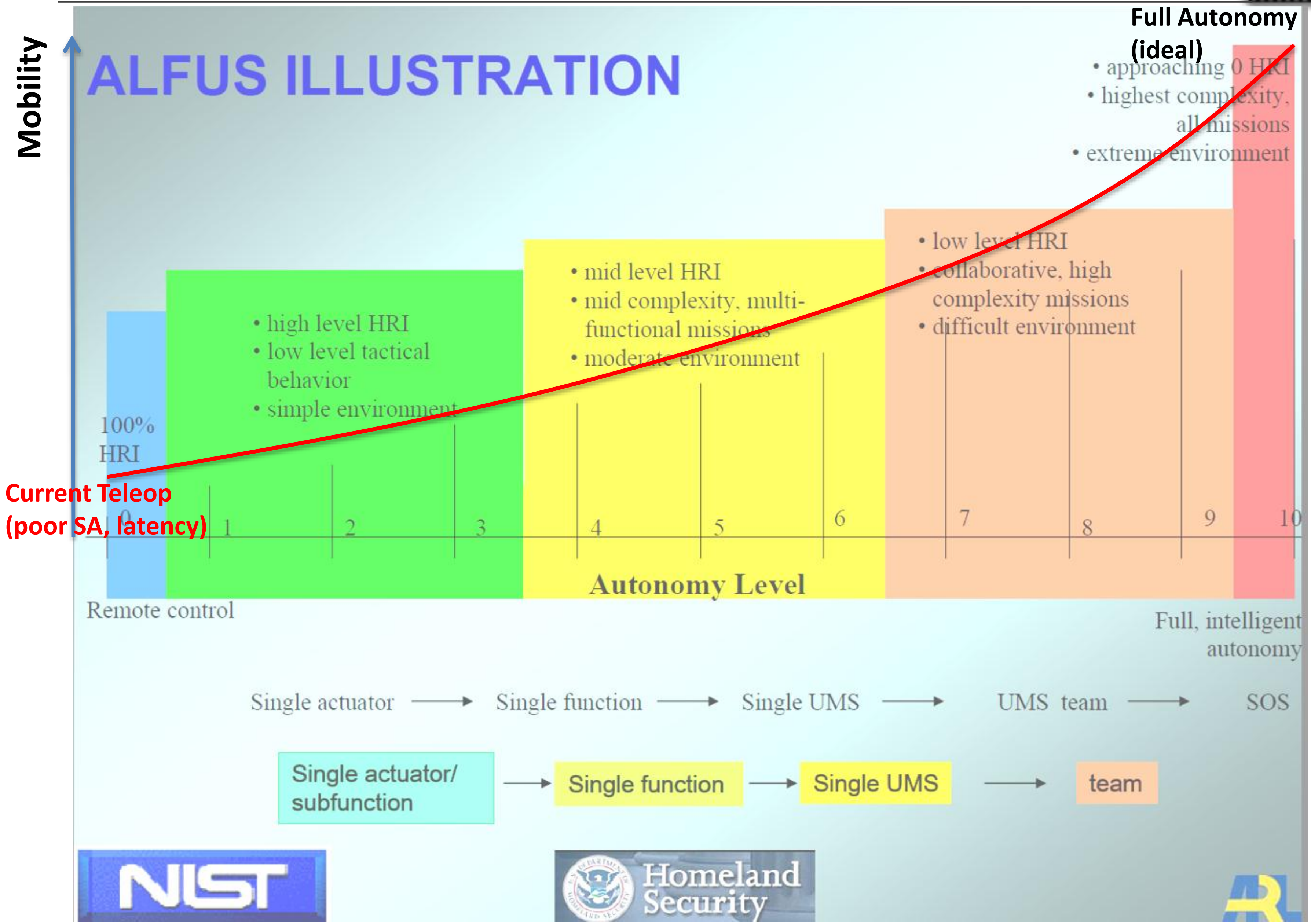
15 m/s, 100m Lidar Range, 10m update spacing

- Green = successful run with numerical value indicating travel time
- Symmetric pattern of uncompensated results indicates that combined latency value is relevant parameter
- Compensating for delays expands region of success
- Travel time for 4s composite compensated delay is equivalent to ~800ms of uncompensated delay

Trade Space Summary

- **Teleop is inferior to full autonomy**
  - Teleop completion time increases with latency
  - Teleop speed decreases with latency
  - Full autonomy speed & time are robust against latency
  - Full autonomy can compensate for latency
  - Full autonomy can work at high speeds
  - However, full autonomy may not be realizable
- **Hence, a high degree of (semi-) autonomy recommended**

Summary


Mobility
Full Autonomy
(ideal)
ALFUS ILLUSTRATION
• approaching 0 HRI
• highest complexity, all missions
• extreme environment
• low level HRI
• collaborative, high complexity missions
• difficult environment
• mid level HRI
• mid complexity, multi-functional missions
• moderate environment
• high level HRI
• low level tactical behavior
• simple environment
100% HRI
Current Teleop
(poor SA, latency)
0
1
2
3
4
5
6
7
8
9
10
Autonomy Level
Remote control
Full, intelligent autonomy
Single actuator → Single function → Single UMS → UMS team → SOS
Single actuator/ subfunction → Single function → Single UMS → team
NIST
Homeland Security
ARL

2. Machine – Human Partnership

Problem: Machine – Human Partnership

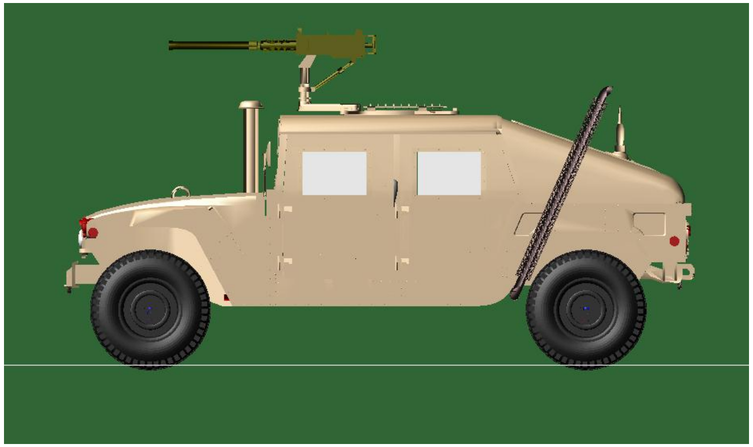
- Q1: Can a remote human in conjunction with a machine beat a human or human team in their environment?
- Q2: How do we identify those military skills that are possible?
- Q3: What feedback (visual: direct, birdseye view, audio) does the remote human need for adequate SA?

Experiment Description

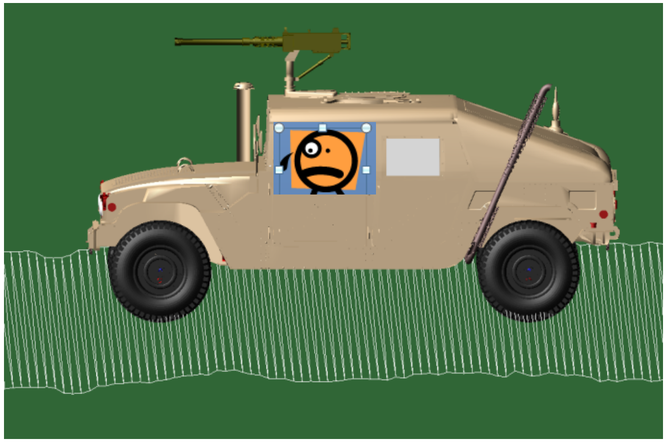
- Investigate the mobility performance of a HMMWV driven by
  - **an on-board driver**
  - **a remote driver**

- Drive the vehicle on **smooth and rough roads** and evaluate limiting performance corresponding to each driving mode

- Compare remote-driver mobility *vs.* on-board driver mobility over each of the two roads



Smooth Road



Rough Road (3 in rms)

Assumptions

- Vehicles driven by on-board driver and remote driver are **identical**

- Remote driver mode has **ideal**
  - Sensor suite
  - Perception / Processor capability
  - Communication network
  - Situational awareness
  - Zero latency
  - Wide bandwidth

CERDEC models can inform changes to these assumptions

OR

CERDEC research can provide these conditions in the future or under certain scenarios?

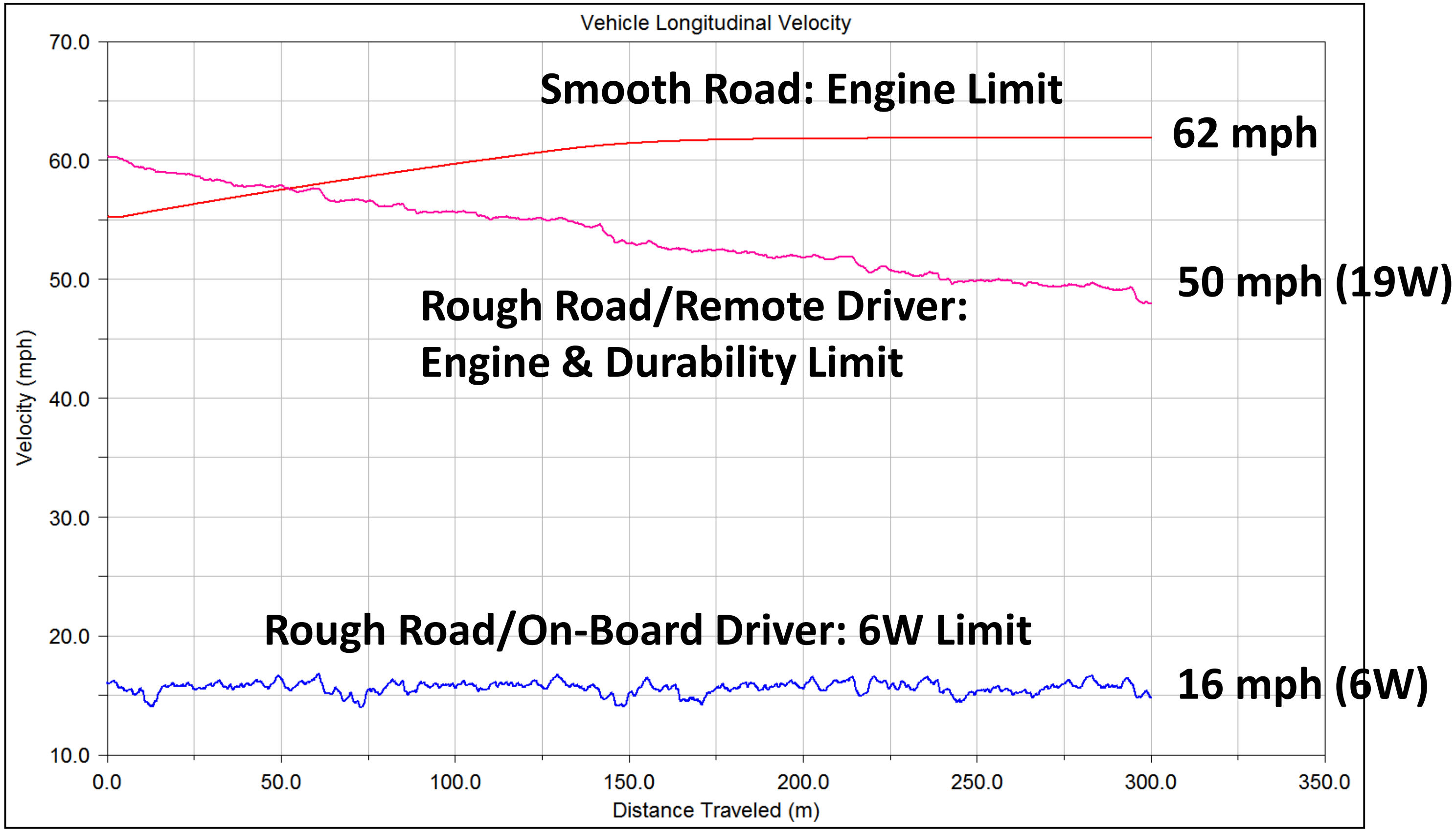
- Benefit
  - Vehicle design elements in manned vehicles can be **modified or eliminated** in unmanned vehicles

Mobility Limiting Conditions

- Vehicle limiting conditions applicable to **both driving modes**
  - Engine limit
  - Brake limit
  - Tire limit
  - Stability limit
  - Structural durability limit

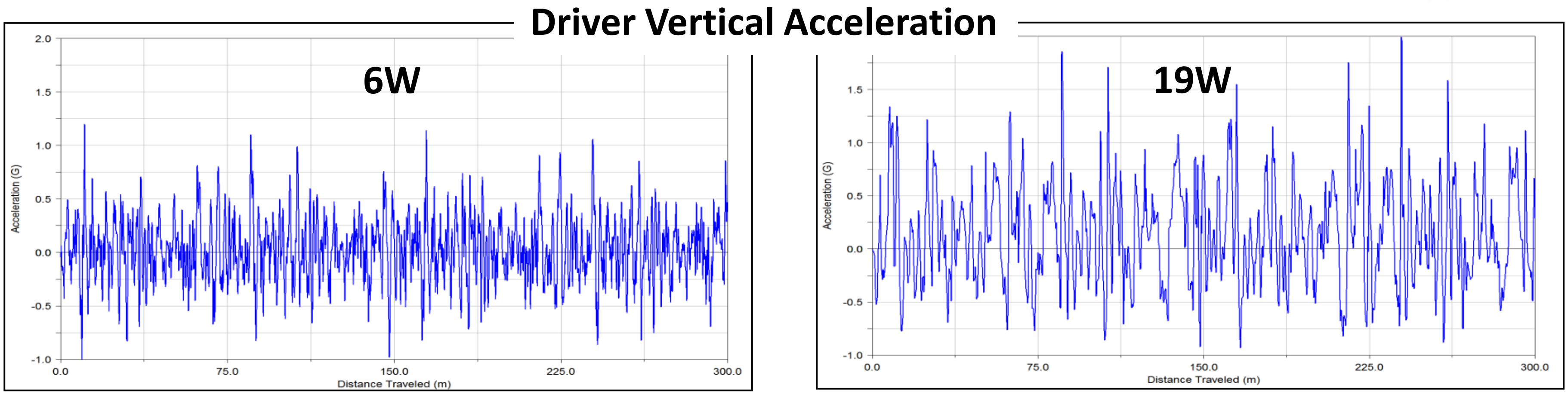
- Driver limiting condition applicable to **on-board driver mode only**
  - Human vibration limit

Speed Profiles of On-Board and Remote Drivers

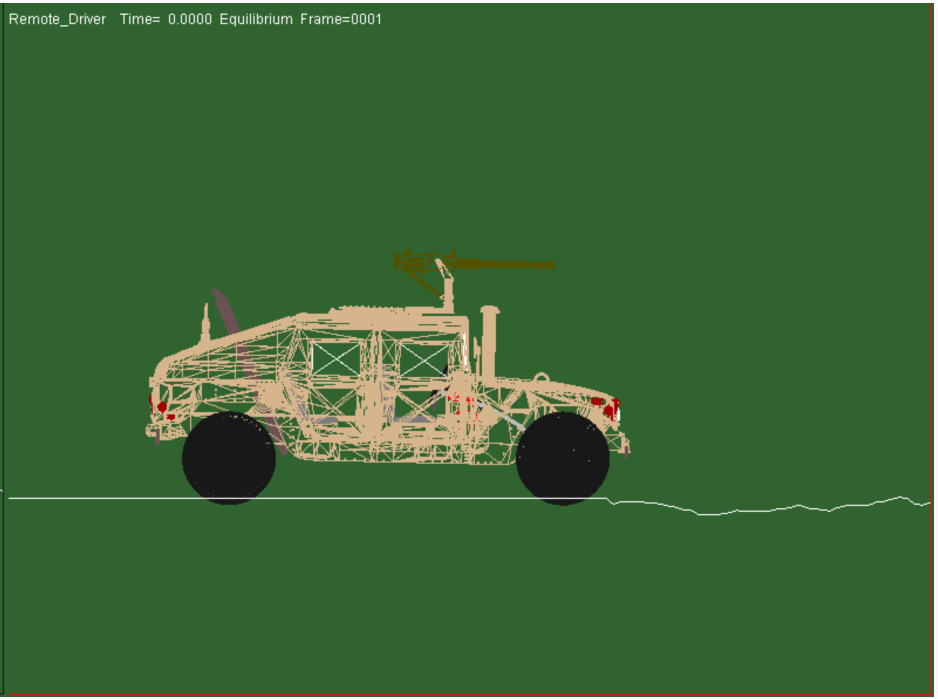


- On-board driver mode is significantly hampered by vibration limit on rough road
- Therefore, remote driver mode performs **significantly better than** on-board driver mode

Rough Road Driving: On-Board vs. Remote Driver


Driver Vertical Acceleration

On-Board Driver (16 mph) Movies **Remote Driver (50 mph)**



Machine – Human Partnership Summary

- It is hypothesized that a remote human in conjunction with a machine can beat a human or human team in their environment.

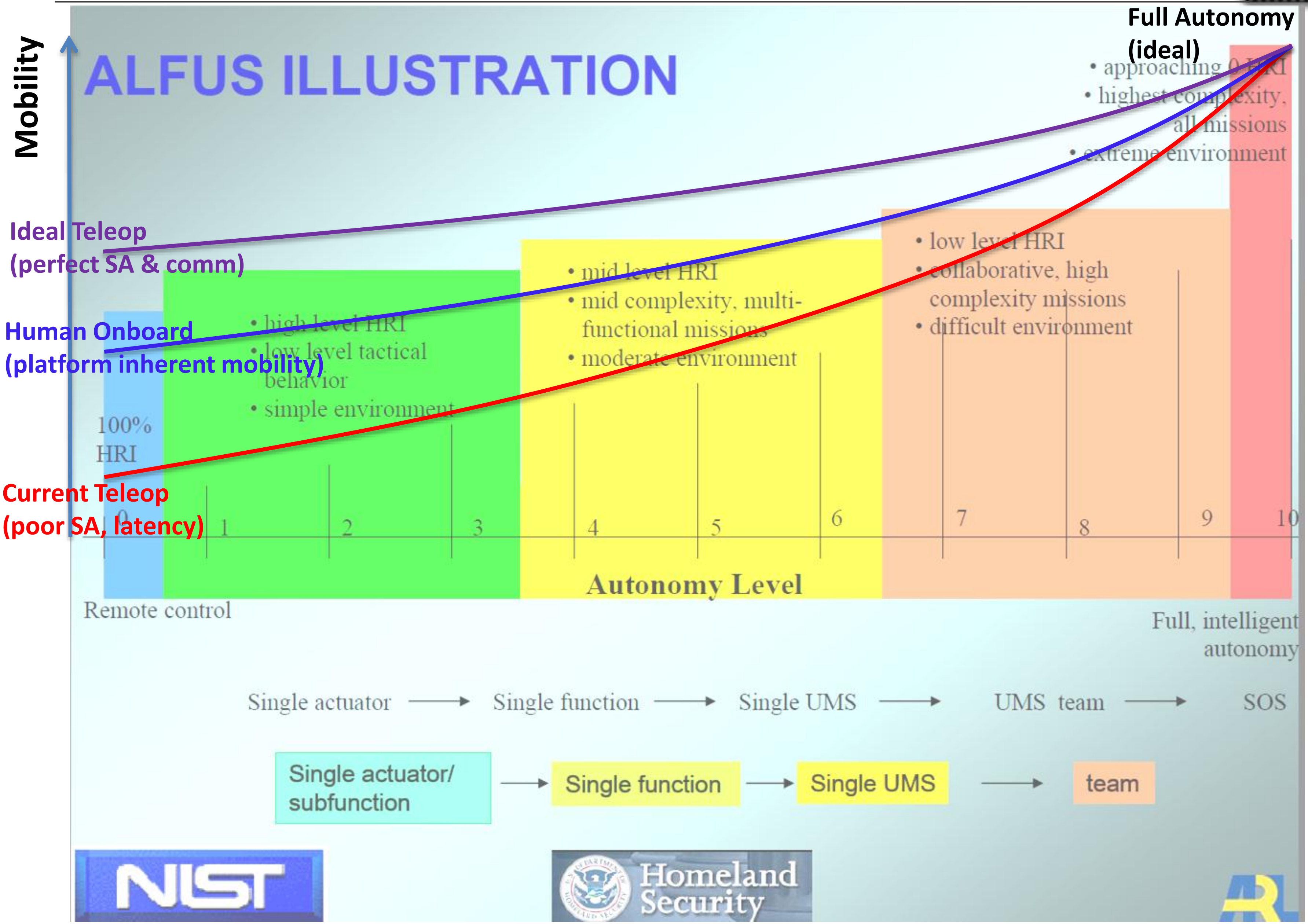
- On smooth roads, remote driver mobility is shown to be equal or better than on-board driver mobility.

- On rough roads, remote driver mode is shown to perform significantly better than on-board driver mode.

- In addition, remotely driven vehicle design can be modified and light weighted resulting in further performance enhancement.

- These results have been derived under **ideal** remote operating conditions such as adequate situational awareness, latency-free communication network, and others as listed.

Summary


Mobility
Full Autonomy (ideal)
Ideal Teleop (perfect SA & comm)
Human Onboard (platform inherent mobility)
Current Teleop (poor SA, latency)
ALFUS ILLUSTRATION
100% HRI
• high level HRI
• low level tactical behavior
• simple environment
• mid level HRI
• mid complexity, multi-functional missions
• moderate environment
• low level HRI
• collaborative, high complexity missions
• difficult environment
• approaching 0 HRI
• highest complexity, all missions
• extreme environment
0
1
2
3
4
5
6
7
8
9
10
Autonomy Level
Remote control
Full, intelligent autonomy
Single actuator → Single function → Single UMS → UMS team → SOS
Single actuator/ subfunction → Single function → Single UMS → team
NIST
Homeland Security
ARL

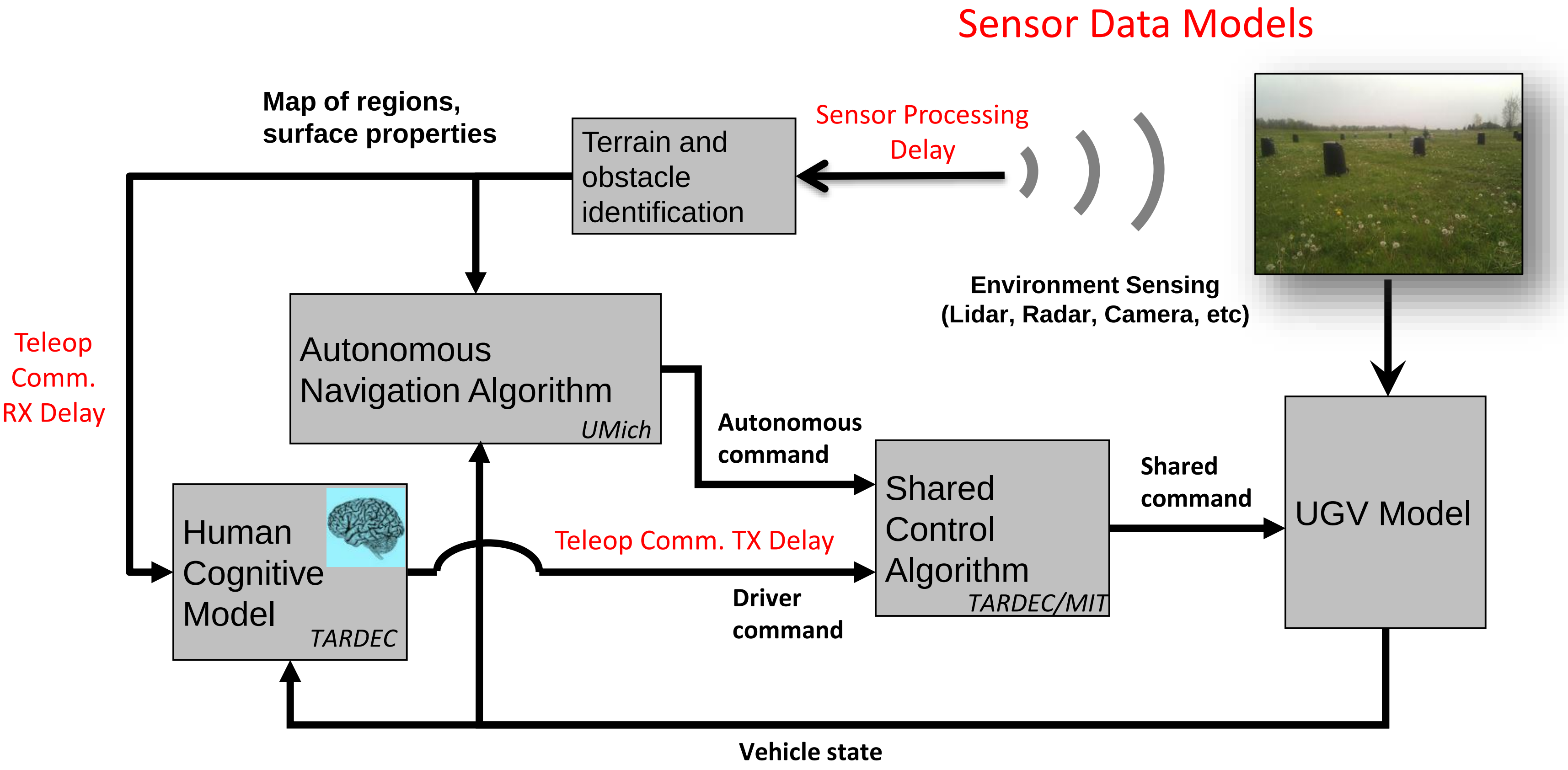
3. Development of Shared Control Simulation Capability

Semi-Autonomous UGV Simulation

- Proof-of-concept software being created at TARDEC
  - Intent is to test feasibility of computer simulation of all components of a semi-autonomous UGV
  - Simulation Components: human operator model, autonomous control algorithm, shared-control algorithm, vehicle and sensor modeling
  - Components being integrated obtained from currently and previously funded work as well as open source software / models

- JPL ROAMS being modified to TARDEC specifications as potential production software for high-fidelity semi-autonomous system research
  - Incorporating new terramechanics models, human operator modeling, autonomous control, and shared-control algorithms tested in the TARDEC proof-of-concept software

Proof-of-Concept Semi-Autonomous Simulation



Sensor Data Models

Map of regions, surface properties

Terrain and obstacle identification

Sensor Processing Delay

Environment Sensing (Lidar, Radar, Camera, etc)

Teleop Comm. RX Delay

Autonomous Navigation Algorithm *UMich*

Autonomous command

Shared Control Algorithm *TARDEC/MIT*

Shared command

UGV Model

Human Cognitive Model *TARDEC*

Teleop Comm. TX Delay

Driver command

Vehicle state

Items in red are areas where CERDEC can inform TARDEC simulations

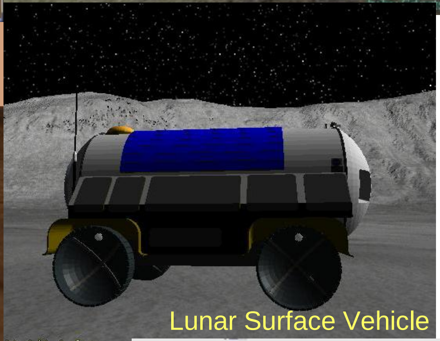
NASA/JPL ROAMS Capabilities Summary

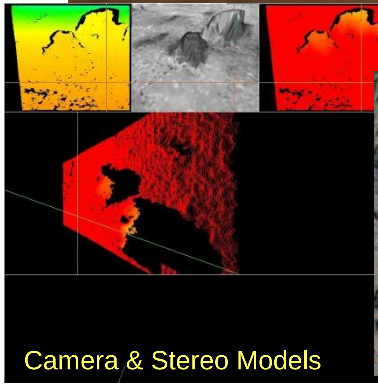
- **Vehicle Platforms:** Single and multi-vehicle simulations; parameterized model templates
- **Motion:** Vehicle mobility, arm models, wheel/soil dynamics – slippage/sinkage
- **Hardware models:** Kinematics, dynamics, motors, encoders, IMU, inertial sensors
- **Camera sensors:** Image synthesis for cameras with non-idealities, rover and terrain shadows
- **Environment:** SimScape synthetic, empirical & analytic terrains, ephemerides interface for sun position
- **Closed-loop visualization:** Dspace 3D graphics (CAD/auto-generated vehicle models), data monitoring
- **Workstation/embedded use:** C++ & Python interface for configuring and closing the loop with software; Stand-alone Monte-Carlo capability.
- **Faster than real-time:** 6x dynamics, sub-second camera image synthesis
- **White and black box** simulation modes

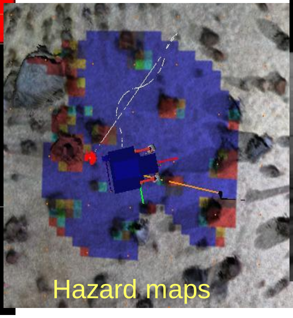

Descending Victoria Crater

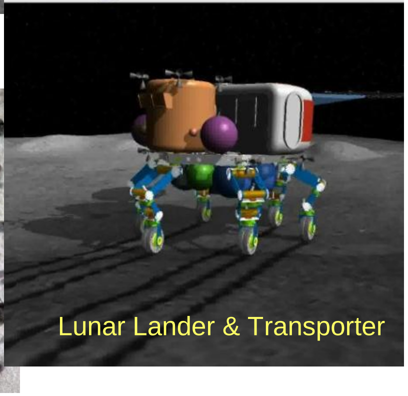

ATHLETE


ATRV Jr


Lunar Surface Vehicle


Camera & Stereo Models

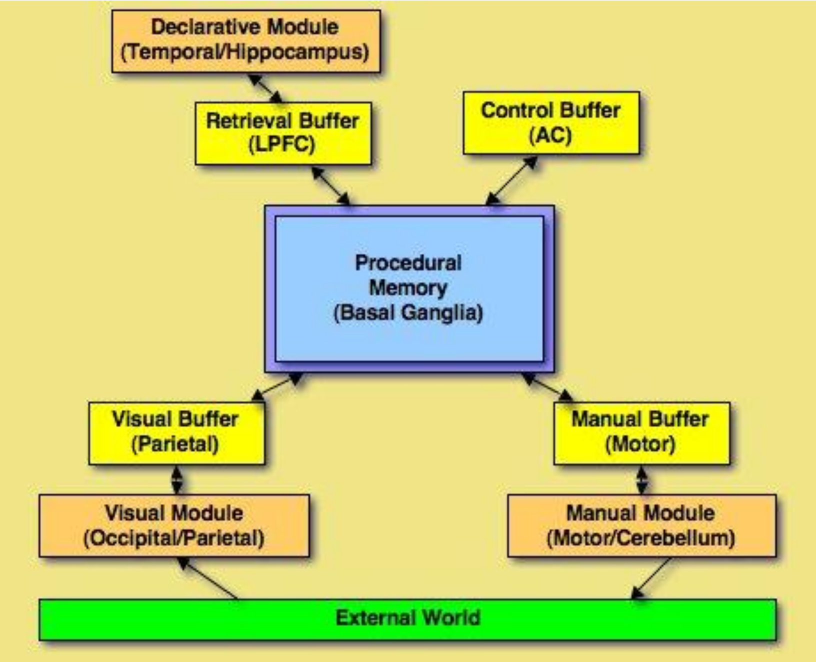

Hazard maps


Lunar Lander & Transporter

Driver Cognitive Model in ACT-R

ACT-R Cognitive Architecture

- High-level computational model of human cognition
- Developed at Carnegie Mellon University by group led by John Anderson
- Almost 40 years of continuous development
- Validated and updated based on human experimentation, brain imaging, and other studies
- Broad base of users
  - US Govt users include: AFRL, ARL, NASA Ames, NRL, NUWC, NIST, ONR, Sandia Natl Lab

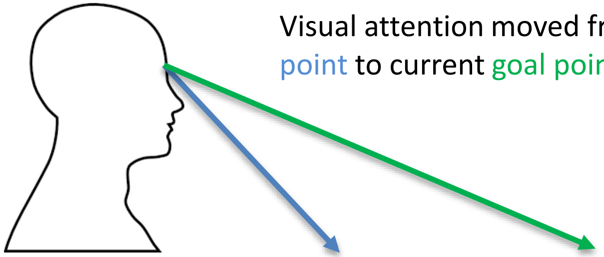


Driver Model

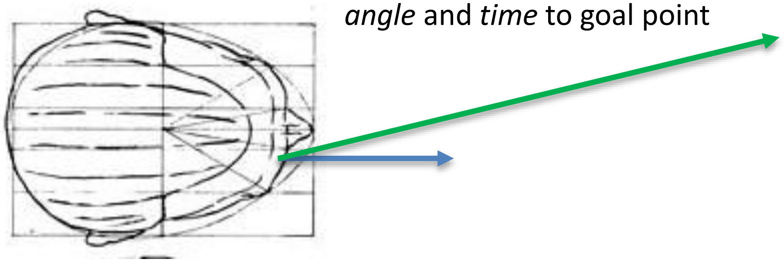
- Existing driver model being leveraged for current effort
- Developed by Salvucci, et al. at Drexel University (http://cog.cs.drexel.edu/act-r/index.html)
- Models sensory/motor performance of human driver or teleoperator

Model Details

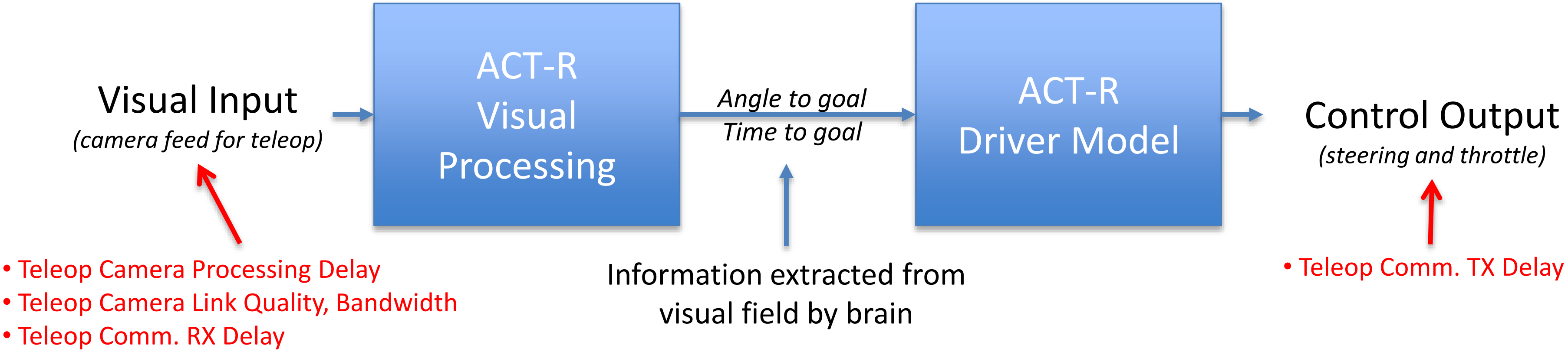
- Driver model incorporates processing of changing visual locations with empirically derived vehicle control laws
  - Visual processing controlled by base ACT-R cognitive model parameters
  - Vehicle control laws part of Highway Driving Task Model



Visual attention moved from near point to current goal point



Visual field processed to extract *angle* and *time* to goal point



- Teleop Camera Processing Delay
- Teleop Camera Link Quality, Bandwidth
- Teleop Comm. RX Delay

Information extracted from visual field by brain

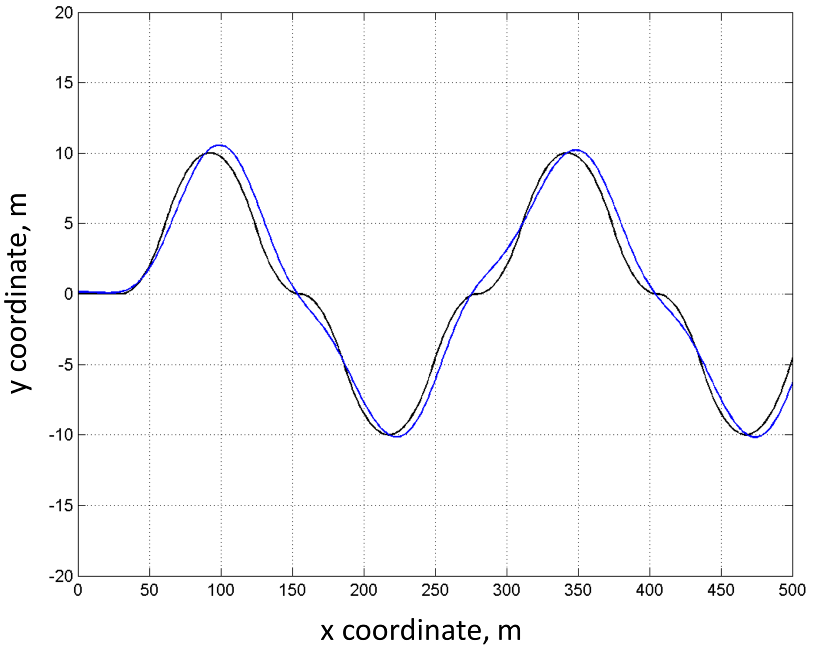
- Teleop Comm. TX Delay

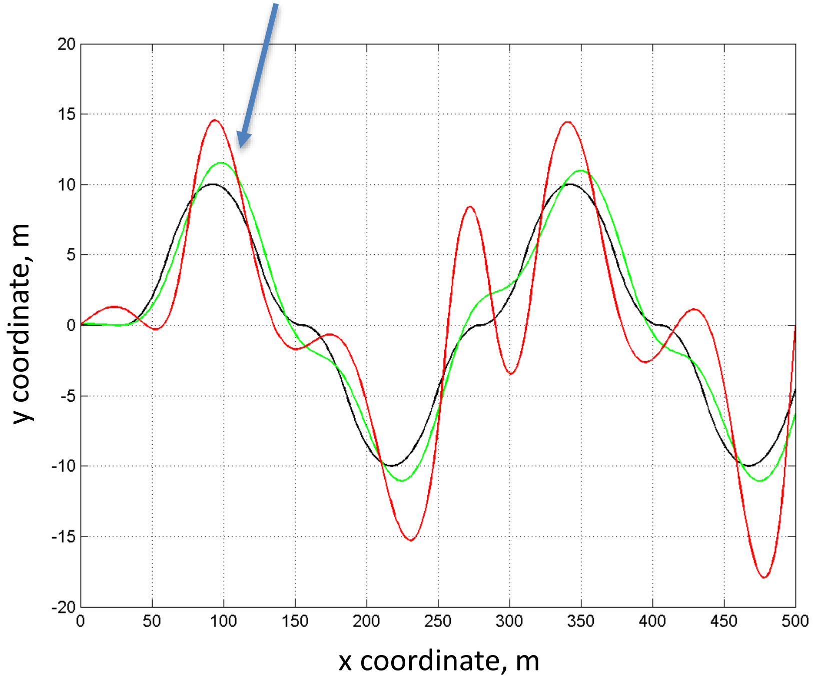
Cognitive Model Path Following with Latency

- **Cognitive model can incorporate latency**
  - **Can incorporate camera link quality in future**
- **Latency effects on cognitive model performance mirror human test results**

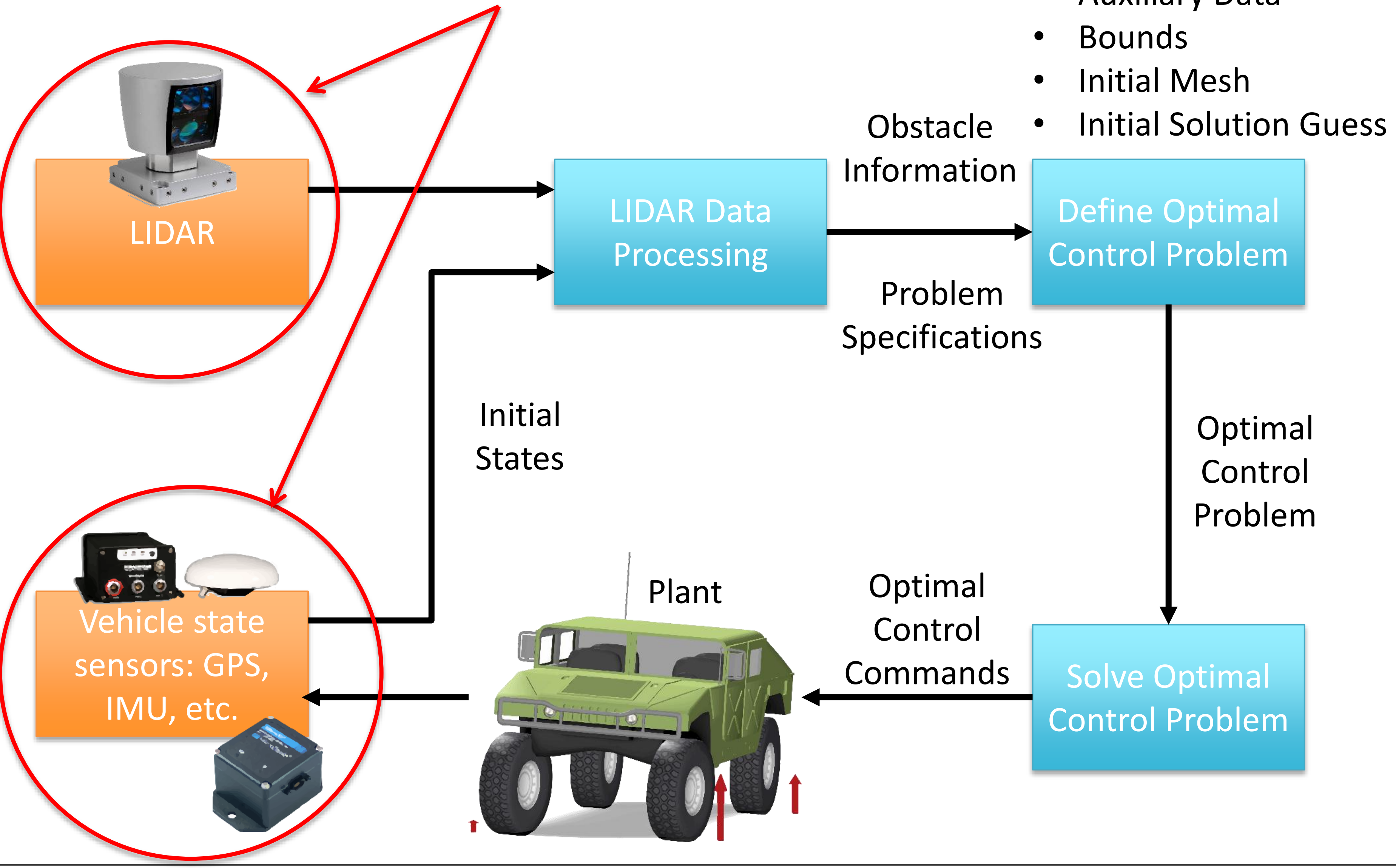
Vehicle speed: 20 m/s
Assume ideal teleop camera quality

Black = goal path
Blue = Cog. w/o delay
Green = Cog. w/ 250 ms delay
Red = Cog. w/ 500 ms delay




Deviations from goal path increase nonlinearly with delay

UMich (ARC) Autonomy Algorithm Overview

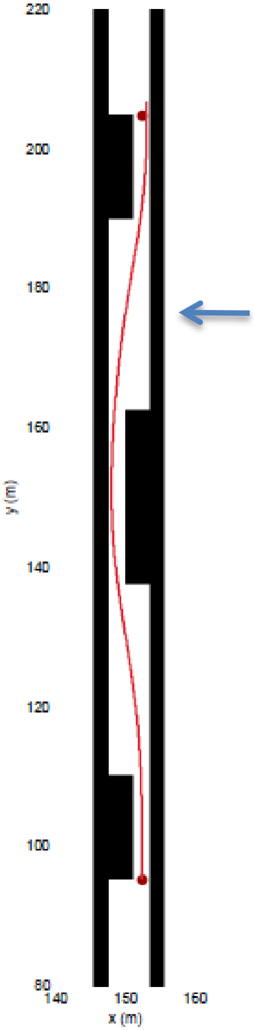


Possible CERDEC Models (Data Quality, Processing Delays)

- Auxiliary Data
- Bounds
- Initial Mesh
- Initial Solution Guess

Effect of Sensor Modeling on Autonomy

NATO Double Lane Change Scenario



Longitudinal speed: 20 m/s
Prediction horizon: 2.5 seconds
Execution horizon: 0.2 second

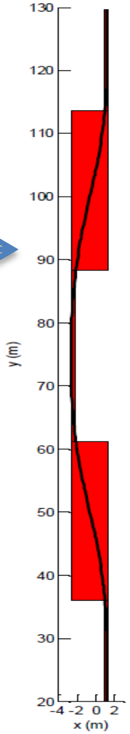
2D LIDAR Model

Algorithm fails

Pseudo-3D LIDAR

(assumes full knowledge out to fixed range)

Algorithm succeeds



Realistic 3D Lidar

Expected performance falls between two extremes

Algorithm result = ?

- **Accurate algorithm assessment and optimization require good sensor models**

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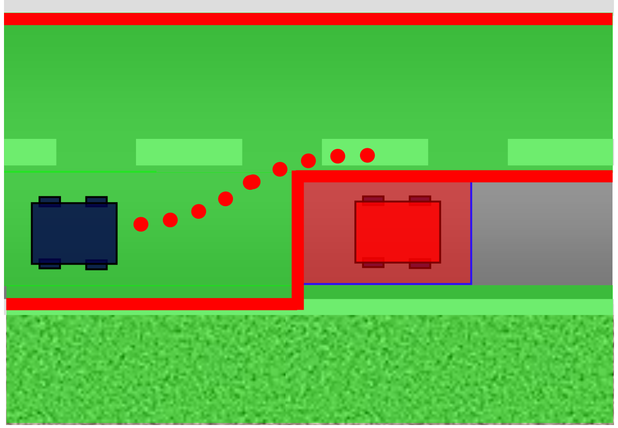
Mobility Scenarios and Metrics

NATO Double Lane Change



Urban Navigation

Off-Road Mobility

- **Mobility metrics**
  - Minimum time
  - Maximum speed
  - Go/NoGo
- **Failure modes**
  - Rollover
  - Immobilization
  - Collision

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Intelligent Vehicle Mobility Simulation Roadmap

KO: 1.1.1, 1.1.4

Model-Based Development of Mobility vs. Latency vs. Autonomy Relation

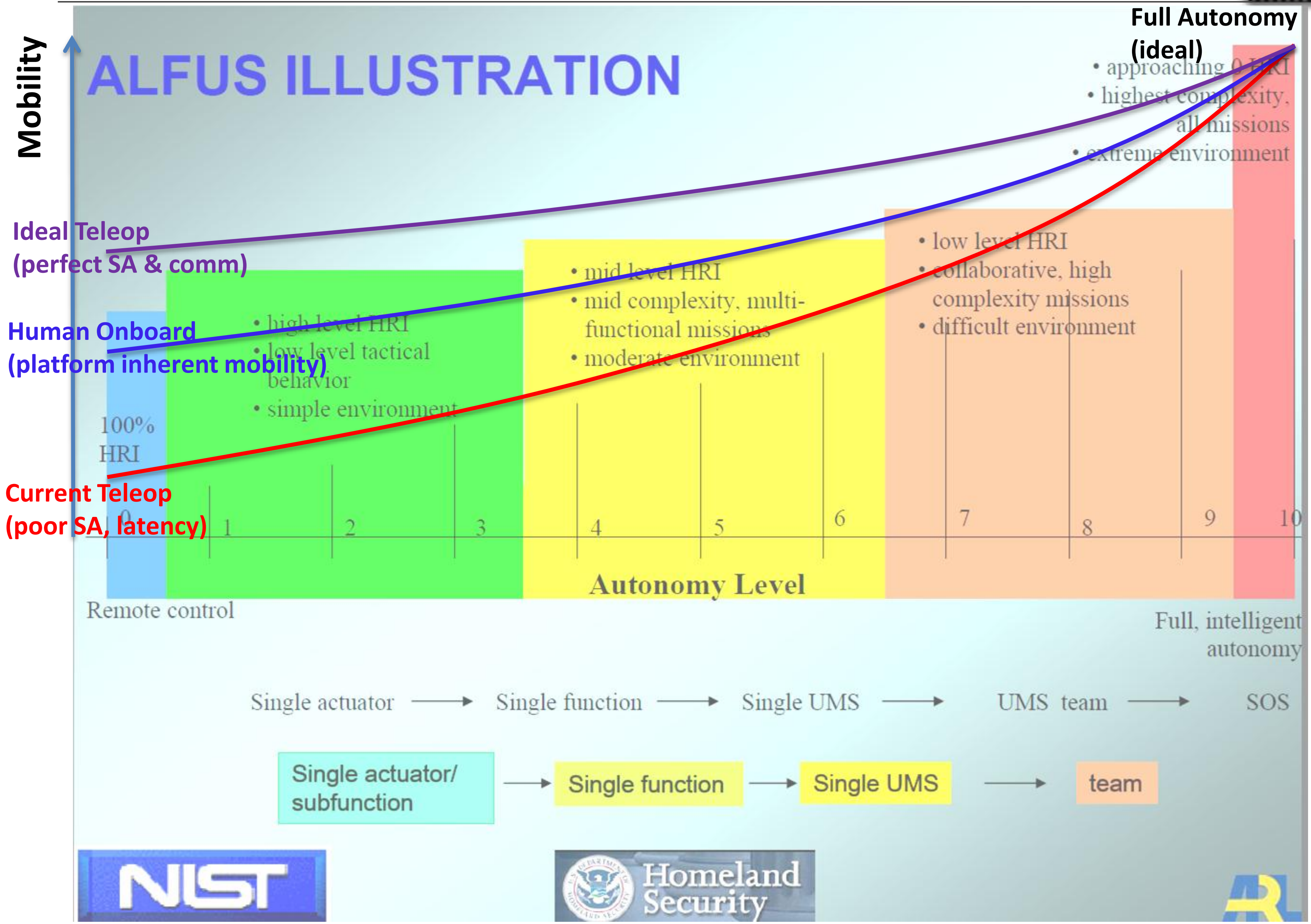
- Platform Mobility **TARDEC**
  - Mobility Scenarios Selection **TARDEC**
  - Mobility Metric Selection **TARDEC**
  - Dynamic Model Fidelity Decision

  - Dynamics Solver Selection **JPL**
  - Terramechanics Approach Development **NATO**
  - Compute Power Selection **ARL TPA**
  - Simulate Mobility Events **TARDEC**
- Communication **CERDEC**
  - Communication Network Selection **CERDEC**
  - Identify Delays and Bandwidth Issues **CERDEC**
  - Implement Delays **UM**
  - Simulate Mobility Events for Various Delays **TARDEC**
  - Analyze Effect of Delays **TARDEC**
  - Mitigate Effect of Delays **UM**
- Autonomy **UM**
  - Select Framework for Shared Control **MIT**
  - Control Algorithm Selection **UM**
  - Driver Cognitive Model Selection **TARDEC**

  - Sensor and Perception Algorithm Selection **CERDEC**
  - Identify Delays **UM**
  - Simulate Mobility Events for Levels of Autonomy **TARDEC**
  - Determine Autonomy & Latency Relationship to Maximize Mobility **TARDEC**

4. Conclusion

Summary



Full Autonomy (ideal)

Mobility

Ideal Teleop (perfect SA & comm)

Human Onboard (platform inherent mobility)

Current Teleop (poor SA, latency)

Needs

CERDEC Expertise

TARDEC Need

	Communication Network Modeling	Sensor Modeling
Teleoperation Simulation	*For use in cognitive modeling and potential mitigation techniques such as predictive displays* Communication link parameters Latency distribution Bandwidth (i.e. video quality) Incorporate scenario (urban, off-road)	*For use in cognitive modeling and potential mitigation techniques such as predictive displays* Sensor Data Parameters Camera model IMU / GPS models Sensor Processing Delays
Autonomy Simulation	*For use if autonomous algorithm is using cloud-based computation or needs to be sent changed mission goals* Communication link parameters Latency distribution Bandwidth (i.e. max data rate) Incorporate scenario (urban, off-road)	*To accurately model inputs to autonomous algorithm and allow for possible mitigation* Sensor Data Parameters LIDAR / Camera / Radar models IMU / GPS models Sensor Processing Delays

Possible Next Steps

Near Term

- CERDEC runs communication network models for current mobility scenarios of interest and provides latency statistics for incorporation into TARDEC models
  - LOS and beyond-LOS links for teleoperation in urban and off-road environments; single operator / single vehicle
  - Latency statistics
- Determine what/whether appropriate CERDEC sensor models can be provided in a form usable by current TARDEC simulation software

Longer Term

- Investigate possibility for co-simulation between CERDEC and TARDEC software for mobility simulation
- Develop complex scenarios and vehicle teaming for mobility simulation