Intelligent Mobility
Modeling and Simulation

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Analytics

Dr. D. Gorsich
Chief Scientist

4 March 2015
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Contents

1. Mobility - Autonomy - Latency Relationship
2. Machine - Human Partnership
3. Development of Shared Control Simulation Capability
4. Conclusion
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

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

CERDEC can provide realistic values

UNCLASSIFIED: Distribution Statement A. Approved for public release. #26550
Teleop Performance of Path Following @ < 5 mph

Completion Time vs. Latency

Speed vs. Latency

178 Runs

UNCLASSIFIED: Distribution Statement A. Approved for public release. #26550
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

<table>
<thead>
<tr>
<th></th>
<th>Sensor Delay</th>
<th>Control Delay</th>
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<tbody>
<tr>
<td>Blue</td>
<td>700</td>
<td>0</td>
</tr>
<tr>
<td>Purple</td>
<td>0</td>
<td>700</td>
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</table>
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 |
|--------------|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|------|------|------|------|------|------|------|------|------|------|
| Lidar Range  |   |     |     |     |     |     |     |     |     |     |      |      |      |      |      |      |      |      |      |      |      |
| 100m        |   |     |     |     |     |     |     |     |     |     |      |      |      |      |      |      |      |      |      |      |      |      |

### 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 |
|--------------|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|------|------|------|------|------|------|------|------|------|------|
| Lidar Range  |   |     |     |     |     |     |     |     |     |     |      |      |      |      |      |      |      |      |      |      |      |      |
| 100m        |   |     |     |     |     |     |     |     |     |     |      |      |      |      |      |      |      |      |      |      |      |      |

**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

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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
Effect of Latency Compensation on Fully Autonomous Mobility

Without Delay Compensation

With Delay Compensation

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

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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

Current Teleop (poor SA, latency)

Full Autonomy (ideal)
- approaching 0 HRI
- highest complexity, all missions
- extreme environment

Autonomy Level
- 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
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

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

CERDEC models can inform changes to these assumptions

**OR**

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

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- 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

Current Teleop (poor SA, latency)

Human Onboard (platform inherent mobility)

Ideal Teleop (perfect SA & comm)

Full Autonomy (ideal)

• approaching 0 HRI
• highest complexity, all missions
• extreme environment

• low level HRI
• collaborative, high complexity missions
• difficult environment

100% HRI
• high level HRI
• low level tactical behavior
• simple environment

Remote control

Autonomy Level

0 1 2 3 4 5 6 7 8 9 10

Single actuator → Single function → Single UMS → UMS team → SOS

Single actuator/subfunction → Single function → Single UMS → team

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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
- Environment Sensing (Lidar, Radar, Camera, etc)

Autonomous Navigation Algorithm

Human Cognitive Model

Shared Control Algorithm

UGV Model

Items in red are areas where CERDEC can inform TARDEC simulations

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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
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
- Models sensory/motor performance of human driver or teleoperator
• 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

**Diagram:**
- Visual Input (camera feed for teleop)
- ACT-R Visual Processing
  - Information extracted from visual field by brain
  - Angle to goal
  - Time to goal
- ACT-R Driver Model
- Control Output (steering and throttle)
  - Teleop Camera Processing Delay
  - Teleop Camera Link Quality, Bandwidth
  - Teleop Comm. RX Delay
  - Teleop Comm. TX Delay

Visual attention moved from near point to current goal point
Visual field processed to extract angle and time to goal point
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)

- LIDAR Data
- LIDAR
- Vehicle state sensors: GPS, IMU, etc.

LIDAR Data Processing

- Define Optimal Control Problem
- Problem Specifications
  - Auxiliary Data
  - Bounds
  - Initial Mesh
  - Initial Solution Guess

Initial States

Plant

Optimal Control Commands

Solve Optimal Control Problem

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Effect of Sensor Modeling on Autonomy

NATO Double Lane Change Scenario

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<tr>
<td>Execution horizon:</td>
<td>0.2 second</td>
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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
Intelligent Vehicle Mobility Simulation Roadmap

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

Platform Mobility
- Mobility Scenarios Selection
- Mobility Metric Selection
- Dynamic Model Fidelity Decision
- Dynamics Solver Selection
- Terramechanics Approach Development
- Compute Power Selection
- Simulate Mobility Events

Communication
- Communication Network Selection
- Identify Delays and Bandwidth Issues
- Implement Delays
- Simulate Mobility Events for Various Delays
- Analyze Effect of Delays
- Mitigate Effect of Delays

Autonomy
- Select Framework for Shared Control
- Control Algorithm Selection
- Driver Cognitive Model Selection
- Sensor and Perception Algorithm Selection
- Identify Delays
- Simulate Mobility Events for Levels of Autonomy
- Determine Autonomy & Latency Relationship to Maximize Mobility

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4. Conclusion
Summary

Current Teleop (poor SA, latency)

Human Onboard (platform inherent mobility)

Ideal Teleop (perfect SA & comm)

Full Autonomy (ideal)
- approaching 0 HRI
- highest complexity, all missions
- extreme environment

ALFUS ILLUSTRATION

Mobility

Autonomy Level

Remote control

0 1 2 3 4 5 6 7 8 9 10

100% HRI

- high level HRI
- low level tactical behavior
- simple environment

Full, intelligent autonomy

- single actuator
- single function
- single UMS
- UMS team
- team

Single actuator

Single function

Single UMS

U.S. Department of Homeland Security

NIST
### CERDEC Expertise

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