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Research Paper

Evaluating mobility vs. latency in unmanned ground vehicles

David J. Gorsich [a],*, Paramsothy Jayakumar [a], Michael P. Cole [a], Cory M. Crean [a], Abhinandan Jain [b], Tulga Ersal [c]

[a] U.S. Army TARDEC, 6501 E. 11 Mile Road, Warren, MI 48397, USA
[b] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena, CA 91109, USA
[c] University of Michigan, Department of Mechanical Engineering, 1231 Beal Ave., Ann Arbor, MI 48105, USA

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ABSTRACT

As the penetration levels of unmanned ground vehicles (UGVs) in military applications increase, there is a growing need to evaluate their mobility across different latencies and various modes of operation ranging from pure teleoperation to full autonomy. State-of-the-art tools to evaluate mobility of ground vehicles do not address this need due to their not accounting for UGV technologies and the associated latencies. Although the trade-off between latency and performance has been thoroughly studied in the telerobotics literature and the results may qualitatively shed light onto the UGV domain, as well, a quantitative generalization is not possible due to the differences in context. Recognizing this gap, this paper presents a functional relationship between mobility and latency in high-speed, teleoperated UGVs under the context of path following. Specifically, data from human-in-the-loop simulations performed in this paper are combined with data from prior studies to span three vehicle types, three courses, and teleoperation latencies ranging from 0 s to 1 s. This combination yields for the first time a diverse data set for the context of path following in high speed, teleoperated UGVs. Based on this data set, empirical relationships are derived to quantify the trade-off between latency versus average speed and lane keeping error. These relationships can be used to establish a benchmark to evaluate the performance of autonomy-enabled UGV systems.

1. Introduction

Mobility of a vehicle refers to its capability to move quickly from point to point. Objective and quantitative assessment of vehicle mobility is an important need for the U.S. Army as well as other practitioners when evaluating alternative ground vehicle technologies. On-road mobility refers to mobility of ground systems on hard, non-deformable surfaces such as concrete and pavement, and many dynamics codes are available for evaluating on-road mobility (ADAMS; Multi-body Simulation – Kinematics and Dynamics – MotionView; Mechanical Simulation – CarSim). Off-road or cross-country mobility refers to ground vehicle mobility over soft and deformable terrains and is a much more challenging problem (Ahlvin and Haley, 1992).

The standard approach used by the U.S. Army to evaluate the mobility of ground vehicles is the NATO Reference Mobility Model (NRMM) (Ahlvin and Haley, 1992). NRMM is a simulation tool developed and validated by the U.S. Army's Tank Automotive Research, Development, and Engineering Center (TARDEC) and Engineer Research and Development Center (ERDC) that aims to predict a vehicle's mobility capability in terms of effective maximum speed under both on-road and cross-country conditions.

One of the important limitations of the NRMM is that it does not offer a methodology and standard for evaluating the mobility performance of unmanned ground vehicle (UGV) technologies. These technologies are also referred to as intelligent vehicle technologies, which involve the use of sensors and information to feed control algorithms to enhance the mobility of the system. These technologies include existing fielded systems such as anti-lock braking systems (ABS), traction control, active suspensions, and track tensioners. UGVs are critical assets for the Army to improve safety and effectiveness; therefore, having a standard means of evaluating their mobility performance is of critical importance. Addressing this need, however, is a challenging problem due to the wide range of operating modes UGVs may have and the large variations that exist in the particular technologies that can be employed to enable a desired mode of operation. Examples include operating under

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* Corresponding author.

E-mail addresses: david.j.gorsich.civ@mail.mil (D.J. Gorsich), paramsothy.jayakumar.civ@mail.mil (P. Jayakumar), michael.p.cole26.civ@mail.mil (M.P. Cole), cory.m.crean.civ@mail.mil (C.M. Crean), abhinandan.jain@jpl.nasa.gov (A. Jain), tersal@umich.edu (T. Ersal).

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teleoperation, semi-autonomous, or fully autonomous modes. This paper focuses on teleoperation.

Teleoperation refers to the mode in which the operator sits in a remote location and sends commands to the vehicle over a wireless network, which the vehicle then executes while sending back sensor information, such as vehicle states or camera images of its surroundings. One challenge with this arrangement is that all networks have some amount of latency, meaning that both the execution of the operator's commands and the transmission of sensor information back to the operator are delayed. These latencies can significantly affect the mobility performance. Hence, it is important to quantify the relationship between latency and mobility performance.

TARDEC has developed notional relationships to illustrate how the mobility performance of ground vehicles may be affected by changes in telepresence and terrain trafficability (Fig. 1). The independent variables are telepresence, which considers latency, bandwidth, and situational awareness, and terrain trafficability, which considers elevation profile and soil strength. The dependent variable is mobility, which may be captured by speed, error, % go/no-go, or other metrics of mobility. The onboard driver surface plot assumes constant telepresence throughout, since the situational awareness of the driver does not change. Human factors such as distraction and fatigue are not considered in this notional relationship. In some scenarios, a vehicle driven by an onboard driver may outperform a remotely operated vehicle. Such situations occur when telepresence is sufficiently poor on all types of terrain, from rough, soft soils to smooth, hard roads. Since the driver is remotely located in teleoperated vehicles, human-related protections, such as armor, and human vibration limits, both of which restrict mobility performance, are no longer needed. Therefore, teleoperated performance may overtake conventional performance once this improvement outweighs any degradation from poor telepresence, such as large latency in the system.

Note that the relationship described above is only notional and data are needed to turn a qualitative analysis into a quantitative one.

Evaluating the mobility of an unmanned vehicle under different latency conditions has been subject to much research using a range of vehicle platforms, including undersea robots (Bulich et al., 2004); ground robots (Luck et al., 2006; Penizzotto et al., 2015; Slawinski et al., 2012; Storms et al., 2017), golf-cart type vehicles (Avatar Teleopeation), and the High Mobility Multipurpose Wheeled Vehicle (HMMWV) (Davis et al., 2010; Zheng et al., 2016). Beyond vehicles, the effect of latency on teleoperation performance has also been studied extensively for robot manipulators (Tamas Heidegger, 2010; Bejczy et al., 1990; Lane et al., 2002; Ferrell, 1965). Methods have also been developed to improve teleoperation performance under latencies (Storms et al., 2017; Zheng et al., 2016; Sheridan, 1993). The general conclusion from these studies is that regardless of the application, communication delays typically negatively affect teleoperation speed (task completion time or vehicle speed) in teleoperated systems. Other performance metrics that aim to quantify how accurately users can control the teleoperated systems are typically also affected negatively by delays. Improvements in performance varied when assistive technologies such as predictive displays were used to mitigate time delays.

Notwithstanding these studies, an important gap exists in the literature. Namely, there is a lack of data for teleoperated vehicles when it comes to high speed (>25 mph) operations. Among the studies reported above, only (Zheng et al., 2016); (Vong et al., 1999) and (Davis et al., 2010) consider high speed applications, but only two delay conditions are analyzed. Therefore, it is unknown how performance metrics would quantitatively change as a function of delay across a range of delay values. It is also unknown what the interaction between mobility, latency and task complexity is for teleoperated vehicles. Even though the dependence of the latency-versus-performance relationship on task complexity has been well-known in the domain of telemanipulators (Sheridan, 1993), it is not yet fully studied for high-speed teleoperated vehicles.

Recognizing this challenge, the goal of this paper is to present a functional relationship between mobility and latency in UGVs that is developed using data collected under the same context. Results are obtained with a simulation framework that is under development to provide an objective and quantitative assessment tool to evaluate mobility of teleoperated UGVs across various latencies under a common context to establish the relationship between mobility and latency. Specifically, a Polaris MRZR 4 is considered

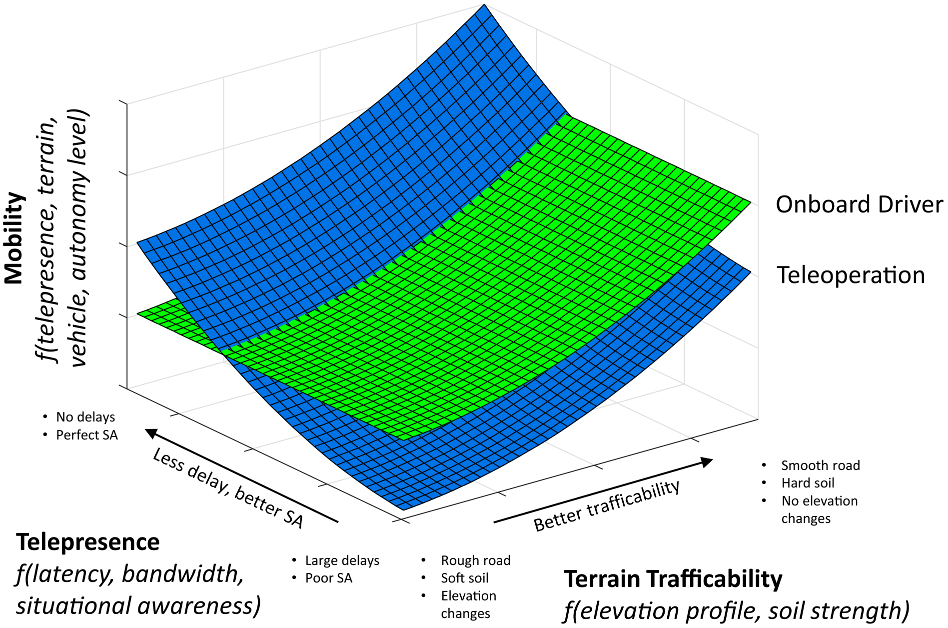

Fig. 1. Notional relationship – teleop vs. human onboard.