EVALUATION OF TELEOPERATION SYSTEM PERFORMANCE OVER A CELLULAR NETWORK

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EVALUATION OF TELEOPERATION SYSTEM PERFORMANCE OVER A CELLULAR NETWORK

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SUMMARY

The ubiquity of cellular networks has exploded over the last half decade making internet access a given when located in an urban settings. On top of this, new technologies like 4G LTE provide higher transfer speeds than ever, permitting streaming of video and other high bandwidth services. Though cellular networks are not new, few studies have leveraged this particular communications method when studying teleoperations, due to the significant bandwidth restrictions.

As a result, this study seeks to understand whether teleoperation could be implemented over regular cellular networks where the bandwidth load that each cell tower is subject to cannot be controlled by the teleoperation system. For this, a prototype system is built using a remote controlled golf cart that hosts a multimedia link between the vehicle and a control station which communicate over the internet.

The system is tested by measuring teleoperation for 3 different tasks of varying degrees of complexity. The results reveal that latency can be low enough to optimally control a remote vehicle. Nevertheless, the performance greatly depends on the network conditions that can vary significantly. The results also indicated that in-situ driving outperformed remote operation.

CHAPTER 1

INTRODUCTION

1.1 Motivation

Teleoperation has been an ever-evolving field in science and engineering since the mid twentieth century. It spans through several fields and depends on collaboration of a wide array of disciplines providing benefits to several industries ranging from sociology to space exploration. Though it may encompasses a plethora of fields, at its roots teleoperation is simply a system that encompasses a master, or operator station; a slave, or remote environment; and a communications link that bridges both sides.

For teleoperations to evolve, advances have to occur on the operator station, the remote environment or the communications link. As time has gone by, more complicated system have risen and enabled development on the master side due to advances in user interfaces, augmented reality or heighten Situational Awareness (SA). Similarly, the slave side has evolved allowing for operators to preform microsurgeries, safe operation in hazardous locations and remote operation in space. All the while the communications link has grown and improved long range control allowing for bilateral control, haptic feedback and other latency driven investigations.

As every facet of teleoperations grows at huge paces, the communications link in particular, spurs growth that leverages wireless technology and grants high degrees of autonomy. Originally, teleoperation was conducted through wired connections between the master and slave systems. As telecommunications evolved into the radio frequency spectrum, wireless control of the master and slave system allowed them to be decoupled. The distance between the systems depended on the extent of the communications infrastructure, where longer ranges required more elaborate setups. With the advent of internet, a democratization of long range communications came that allowed for organizations with reduced infrastructure capabilities to connect over longer distances. As communication strategies gradually improved, data transfer rates grew and end to end latencies decreased. However, the “last mile” implementation of wireless systems still depended on installing hardware that have short range limitations, like Wi-Fi.

A sub category that has exploded in the recent years, seeking to reduce or even eliminate the “last mile” problem, is cellular technology. Though not new in wireless communications, the advent of 4G has significantly improved data transfer speeds and latencies, allowing teleoperation to open up new avenues and demographics that were previously unattainable due to infrastructure and cost restraints (Ericsson, 2015).

As will be seen in Chapter 2, some studies have already delved into teleoperation via cellular networks, using 3G and 4G protocols successfully. But what is understood as a successful implementation of a teleoperated system in some investigations does not imply that the technology is capable of reliably and effectively controlling a remote system. Hints of this can be inferred when studying relevant author’s conclusions, where recommendations to further research connection loss protocols or implementing more autonomous algorithms imply difficulties in controlling the system with a cellular communications link.

With this in mind, it is intent of this study to further delve into cellular teleoperation and determine to what extent the use of cellular networks can be leveraged.

1.2 Objectives

The main question behind the research conducted herein is whether a cellular network offers a reliable connection capable of properly controlling a remote vehicle. Many investigations tend to reduce this down to whether or not the system has enough bandwidth or a low enough latency. However, this sometimes tends to be subjective and limits for latency can range from just a few tens of milliseconds to over five hundred milliseconds and a similar situation arises with band width.

Moreover, just measuring certain aspects of the connection does not guarantee that the operator is capable of effectively driving a remote vehicle. In other words, it is possible for the system to perform nominally when measuring the through-put in megabits per second and time delay in milliseconds, but these parameters speak very little about the resolution that the operator observes, how the remote environment is being interpreted by the driver or whether other aspects of teleoperation are causing strains on operator performance.

Understanding that there are benefits and limitations to any method that seeks to measure performance, this study believes that metrics used to interpret how well an operator executed a task may better determine how well the entire system allows for effective and reliable control of a teleoperated system. This way, system reliability is indirectly measured by assessing the operator’s global performance.

The principle hypothesis of this investigation is to determine whether “a vehicle can be controlled over a 4G LTE network, streaming HD video feedback”. Generally speaking, two issues have to be successfully complete for the hypothesis to be considered valid. The first relates to the quality of the visual feedback that the system incorporates. In this case, it is expected that the camera streams captured on the remote environment be of the highest quality possible, and for these to be able to be transmitted back to the operator. The second relates directly to the performance that the drivers show while operating the system. If both issues are achieved successfully, then in can be said that the principle hypothesis is accepted as true.

On top of this, a secondary hypothesis is stated later in this thesis regarding to how performance is affected due to camera position. Due to how the teleoperation system is built, this investigation has the unique opportunity of comparing operator performance in function of the positions of the cameras. This is further explained in Chapter 3, but generally speaking, the system can be configured with cameras in different locations providing the driver with two points of view while completing each task. Because of this, a comparison of performance can be established between different points of views and subsequently, if a statistically significant difference exists, one point of view can be said to be better than the other.

1.3 Thesis Structure

Intent on accomplishing the objective detailed in the previous section, this thesis is structured in the following manner. Chapter 2 details relevant information regarding teleoperation, research that others have performed regarding teleoperation with cellular networks and how others have measured performance. Chapter 3 describes the teleoperation system built in this thesis used to determine the validity of the principle hypothesis, explaining each sub category and how they all tie together. Chapter 4 details the experimental design and the statistical tools used to analyze the experiments that help determine the validity of the principle hypothesis. Chapter 5 shows the results obtained from the experiments and delves in a discussion of the observed results. Finally Chapter 6 concludes this investigation by summarizing the works conducted in this study and detailing possible future works.

CHAPTER 2

LITERATURE REVIEW

Though one could perhaps wright a whole book detailing every step that teleoperation has taken and how its offspring's have shaped current research, this study is mainly concerned in providing basic concepts of what teleoperation is so that the reader can understand the decisions involved that guide this investigation. With this in mind, a brief overview of teleoperation methods and current applications are presented in this chapter. Common methods for measuring teleoperation quantitatively and qualitatively are also presented and discussed. Time delay issues are detailed while current research and experiments related to cellular teleoperation are presented highlighting principle advantages and difficulties.

2.1 Teleoperation

Teleoperation has existed for quite some time and can be traced back to the mid-1940s, as was done by (Sheridan, 1995) referencing a publication by Raymond C. Goertz who built a master slave device that manipulated radioactive material from a shielded distance. Others, who offer broader definitions of teleoperation, state that it can even be traced back to prehistoric eras, arguing that poking a fire with a stick is a form "manipulation from a distance" (Liciardopol, 2007).

Gradually, Goertz's mechanically operated system evolved to an electro mechanical servo system with feedback, becoming the first modern electromechanical teleoperated system. From here, teleoperation exploded and similar structures have been developed to explore or control remote environments ranging from underwater to space exploration.

The definition of teleoperation can vary from very specific to practically unbounded, but one particular definition resonates with this author is:

'Teleoperation means "doing work at a distance", although by "work" we mean almost anything. What we mean by "distance" is also vague: it can refer to a physical distance, where the operator is separated from the robot by a large distance, but it can also refer to a change in scale, where for an example a surgeon may use micromanipulator technology to conduct surgery on a microscopic level. Teleoperations comprise a robot technology where a human operator (master) controls a remote robot (slave)….' (Liciardopol, 2007)

From here (Liciardopol, 2007) goes on to describe how a teleoperation system is composed and provides interesting details into frequent difficulties encountered in teleoperation. What is interesting, though, is that even in high level definitions little clarity exists when defining this type of technology. This vagueness eventually trickles down into even the most common issues studied in teleoperation and drives researchers to develop a wide array of possible interpretations to measuring performance.

Driven by this ambiguity, and depending on the author being reviewed, teleoperation can be categorized into different subcategories. Commonly, authors tend to classify teleoperation depending on the method of control in the remote environment. Though some differ slightly, a good categorization of control methods is provided by (Swanson, 2013), who separates the system in to 5 categories:

- Master – Slave
- Supervisory – Subordinate
- Partner – Partner
- Teacher – Learner
- Fully Autonomous

These will be explained in the following section.

2.1.1 Master-Slave

As described by (Swanson, 2013), basically every teleoperated system is composed by two main environments, Operator and Remote, linked together by a communications protocol. In Figure 2-1, one can view a general diagram that explains how a Master – Slave system is organized.

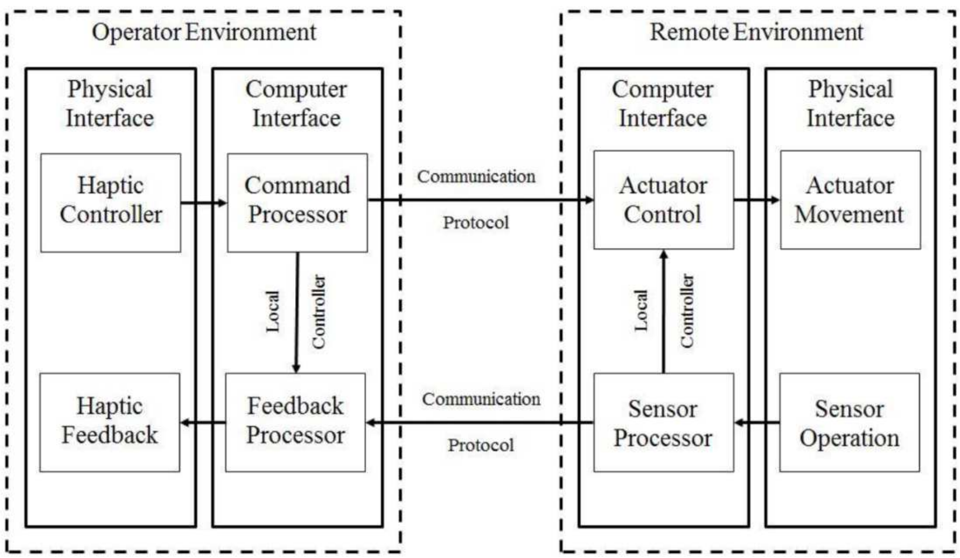

Figure 2-1 Master-Slave System *(Swanson, 2013)*

In essence, the operator inputs command through the physical interface to the command processor that transmits the signals to the actuator controller. This in turn commands the actuator movement generating a reaction in the remote environment.

Simultaneously, the sensory feedback is collected and passed to the sensor processor to be sent back to the feedback processor in the operator environment. Subsequently these are passed to the operator and a response is triggered starting the cycle again.

2.1.2 Supervisory – Subordinate

Another common category used in teleoperation is supervisory control. Here the general environments are similar to the Master – Slave system, but the control blocks that compose these are changed so as to allow for different levels of autonomy.

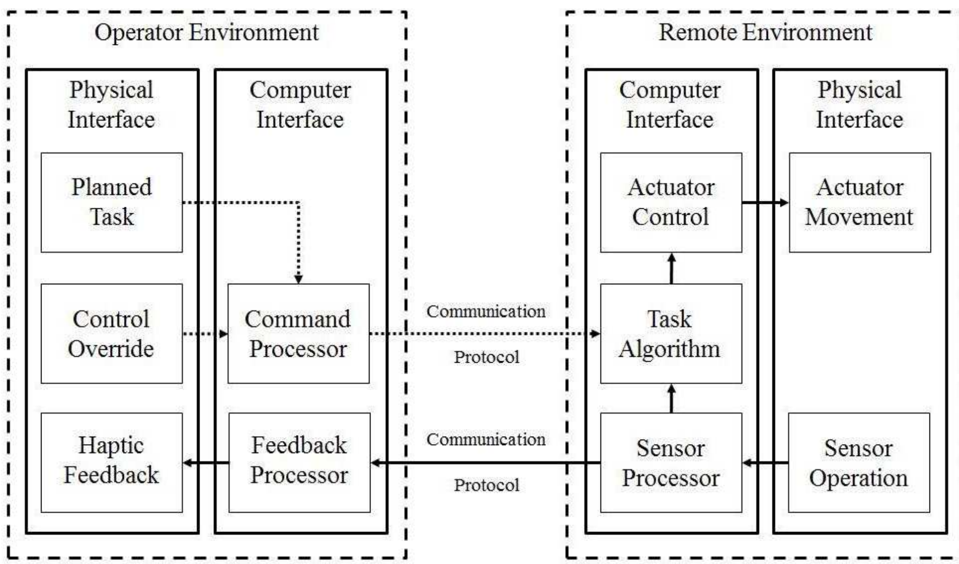

Figure 2-2 Supervisory-Subordinate System *(Swanson, 2013)*

The remote side is tasked with the majority of the computing power in order to allow the algorithm to perform preplanned tasks. Feedback is continually sent to the operator environment so as to verify that the system is operating correctly, and in the event of corrective measure being need, the operator can send instructions to the task algorithm to complete.

2.1.3 Partner – Partner

The Partner – Partner configuration is unique due to the change in paradigm, where the action takes place in the operator environment instead of the remote environment. Here, the remote environment supports the actions taken by the operator through sensing and corrective signals transmitted back to the operator environment.

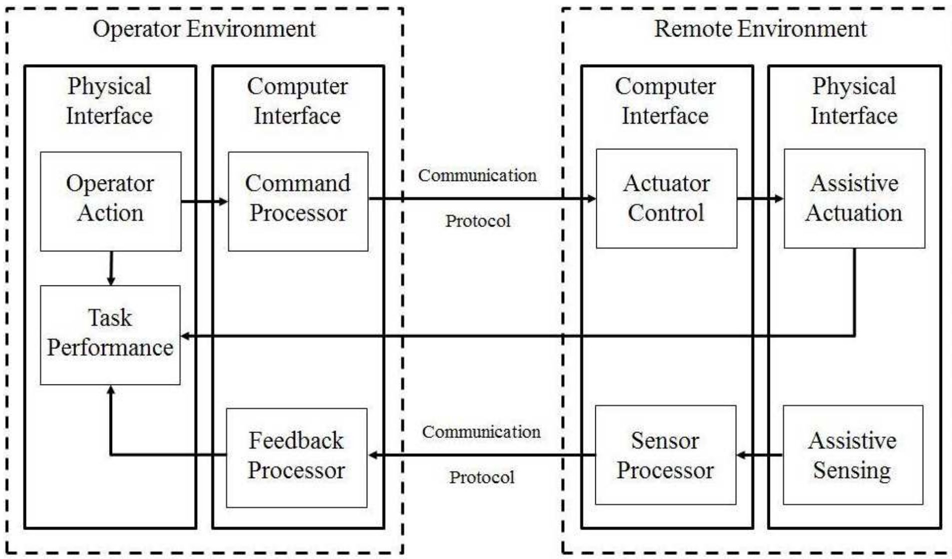

Figure 2-3 Partner-Partner System *(Swanson, 2013)*

2.1.4 Teacher – Learner

The teacher learners system is a mix between supervisory control and master slave architecture with the exception that the remote environment includes a control block that has a learning algorithm. This algorithm is in charge of progressively taking more control of the remote side so as to ease operator strain.

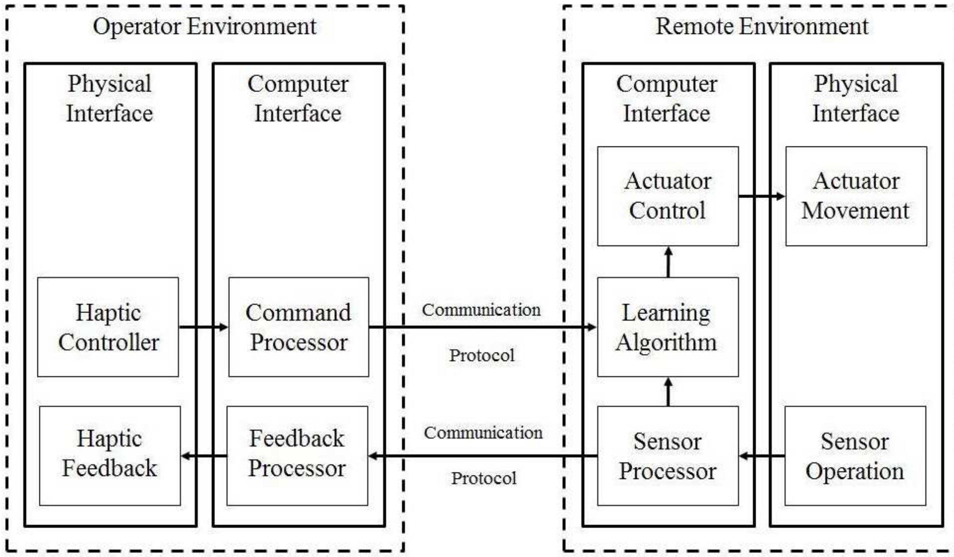

Figure 2-4 Teacher-Learner System *(Swanson, 2013)*

2.1.5 Fully Autonomous

Lastly, autonomous remote control of the vehicle allows for the remote system to guide itself, being able to complete tasks without any supervision form the operator environment. However, feedback is still available to the operator.

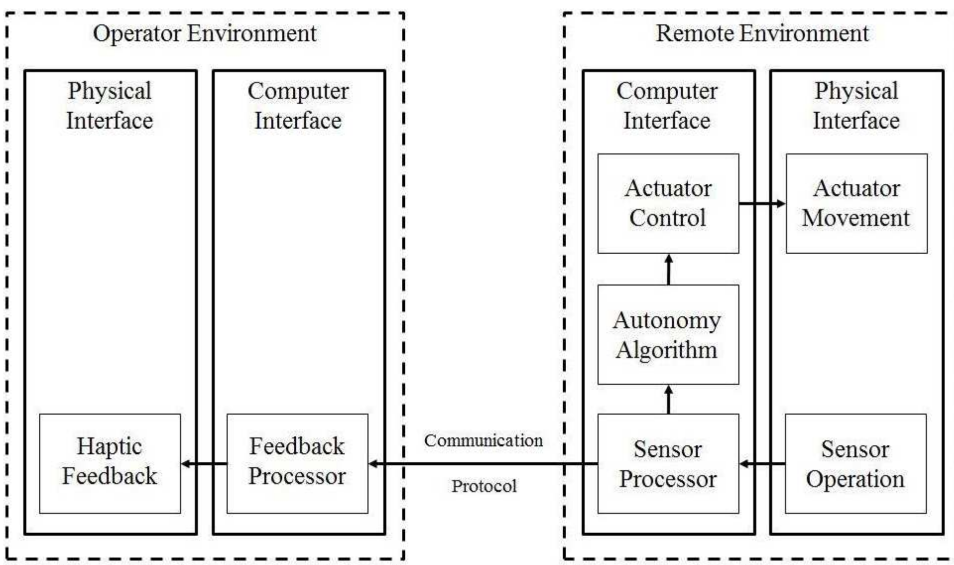

Figure 2-5 Fully Autonomous System *(Swanson, 2013)*

2.1.6 Current Applications in Teleoperation

As time has transpired and new methods for remotely controlling robots have evolved, ever more uses have been developed for teleoperated system. Most would be familiar with larger media displays such as NASA's moon and mars explores, but several industrial applications exist that are essential to productivity. Current applications worth mentioning are detail in the following section.

2.1.6.1 Space Applications

Space provides a unique environment for teleoperation. Due to the limiting circumstances astronauts face while in orbit, or even on earth, remote operation of tools and vehicles is fundamental. Key examples are; vehicles sent to other planets, like the mars rover, or crane arms used for space repairs or docking procedures. The author (Liciardopol, 2007) divides space teleoperation into 3 main categories:

- Space exploration robots: robots sent as a first interaction mission for gathering initial telemetry. Examples of this are:
    - Landing robots (Sojourner (NASA), Rocky I-IV (NASA), Lunakhod I (Russia))
    - Explorer probes: (Voyager (NASA))
    - DEEP Space Observers (Hubble Observatory)
- Satellites: robots that provide communication, weather forecasts, GPS, among other functions.
- Outer-space robot arms: that provides an extension that may execute tasks without requiring humans to be exposed to hazardous situations.

2.1.6.2 Military/Defensive Applications

The military has, for a long time, used teleoperation in several different ways with a primary focus of reducing human exposure to dangerous situations. Some of the most advertised applications are Unmanned Air Vehicles (or UAV) for reconnaissance and long range strike missions; using radio or satellites as a communications medium. Another known application is Unmanned Ground Vehicles (or UGV) used for reconnaissance, route clearing or land-mine detection. One of the newer models used in this application is SARGE (Liciardopol, 2007), that is commonly equipped with state of the art stereo vision or auxiliary sensors so that the operator can execute the tasks quickly and efficiently.

2.1.6.3 Toxic environments

In toxic or radioactive environments, human presence is generally avoided or even restricted. Due to this limitation, an overwhelming amount of tasks specific teleoperated machines have been developed for executing tasks that human cannot complete, due to the dangers of the remote environment (Cui, Tosunoglu, Roberts, Moore, & Repperger, 2003).

2.1.6.4 Telerobotics in Forestry and Mining Applications

Due to the unique risks that that forestry and mining operators face, several efforts have been made to design and build specialized equipment with teleoperation capabilities. An example of this is the Centrauroid robot developed by the Helsinki University of technology; whose particular design emulates human maneuverability in complex forest terrain (Liciardopol, 2007). Some other applications that may be seen in mining are:

- Heavy machines: such as tunnelers, excavators and crushers that can be remotely operated enhancing plant autonomy and reducing human exposer.
- Exploratory robots: that allow for inspection of risky mines from secure locations, such as the Groundhog developed by the robotics institute at Carnegie Mellon (Morris, 2005).
- Rescue robots: that allow search and rescue operation potentiality unstable mines in events of collapse or other unsafe circumstances, such as the cave crawler, also developed by Carnegie Mellon. (Baker, 2005).

2.1.6.5 Telesurgery

Teleoperation has even been seen in the medical industry allowing physicians to perform delicate tasks that were previously unimaginable for humans. As previously defined, “remote” can be understood as a large distance between the operator and environment or even as a “difference in scales”. Particular examples of these two meanings are the studies carried out by NASA (Liciardopol, 2007) and (Korte, et al., 2013) or by the Da Vinci Surgical system. In the case of NASA, they wanted to understand how much time delay was acceptable in a low orbited teleoperated surgery, concluding that delays of more than 1,5 seconds could not be accepted. Or the surgical system developed by Da Vinci Surgery that allows for physicians to conduct micro surgery in patients with minimal incisions.

2.2 Quantifying Teleoperation

Having seen the several ways that teleoperation systems can be constructed and the plethora of different industries that depend on properly configured systems, it becomes apparent that classification of these systems in function of their performance is required for proper comparison and decision making. However, as may be expected, no one method exists when measuring teleoperation performance; where commonly each investigation determines a quantification strategy based on their goals and objectives. Due to this, a survey of current investigations is completed and a brief description of the different methods encountered is described.

By far, the most common form of quantifying teleoperated systems is by analyzing the time domain response of actions on the master side and studying their reactions on the slave side, (Swanson, 2013). While other popular method often used in unison with the previous, is to analysis the systems in the frequency domain (Tanner & Niemeyer, 2005). Though these methods provide good comparison of how the system is performing when stimulated with predetermined signals, they don’t always reflect how users are conditioned by other factors, such as time delay of the video source, resolution of the video feed, variability of the time delay or any other factor not included in their study.

Strictly speaking, these factors are not commonly associated with teleoperation but rather studied as a part of telepresence. None the less, performance in teleoperated system is believed to be directly proportional to telepresence. Due to this, this investigation also delves into telepresence and presents different methods for quantifying it.

When thinking of telepresence, a lot less ambiguity surrounds its definition. An overwhelming number of studies define it as “the ability of the remote environment to be relayed back to the operator” in a way the he is optimally immersed (Preusche & Hirzinger, 2007). At its most basic, telepresence is any feedback that the system provides its user. This may range from videos streams sent back, force reflection of the environment or even audio queues that give the user a sense of where objects may be located. Though at first glance these concepts may seem easy to quantify, no one method exists when measuring said concepts. Thus, most research that investigate these factors tend to focus on indirect metrics or the Situational Awareness (SA) that the operators have while manipulating the teleoperated system. Situational Awareness may be understood as the perception of the environment over time and space.

2.2.1 Quantification Strategies for Teleoperation

Since quantifying performance of a teleoperated system by just analyzing the time or frequency domain does not offer a holistic view of performance, this investigation has decided to review methods that try to determine global metrics of overall performance or telepresence. With this in mind certain studies that apply this type of quantification are reviewed.

An example of the previous can be seen in (Halme, Suomela, & Savela, 1999), where the authors compare different camera setups, such as: stereo-vision with head tracking, mono-vision and video display on a screen. Their hypothesis is that “the more expensive the configuration of a video setup is then the better the operators can perform required tasks”. To quantify this, they submit several subject to different tasks and monitor how many errors they make and how long it takes them to complete the required tasks. Additionally, each participant is then required to complete a personal opinions questionnaire of their experience. They determined that while the more sophisticated setup did provide better results (less total error deviations and times) they marginally outperformed simpler configurations. Furthermore, in some tasks, it did not matter how complex the setup was and not benefit was perceived between setups. Nevertheless, they conclude that stereo vision and head tracking equipment on the remote vehicle does provide better overall control based on user feedback.

Another study that also researches how camera positions influence teleoperation has an interesting hypothesis. This Investigation (Saakes, Choudhary, Sakamoto, Inami, & Igarashi, 2013) believes that placing the camera on an unmanned aerial vehicle will provide the operator with a larger perspective and thus give the driver a higher sense of telepresence. Again, this study indirectly measures telepresence & teleoperation based on performance by quantifying the amount of errors an operator makes as he passes through a maze and total time to complete the experiment. After completing the experiments and tallying the results, the researchers statistically validate their hypothesis by comparing the means of the metrics to different camera positions and determine that overhead views are better when compared to front facing cameras.

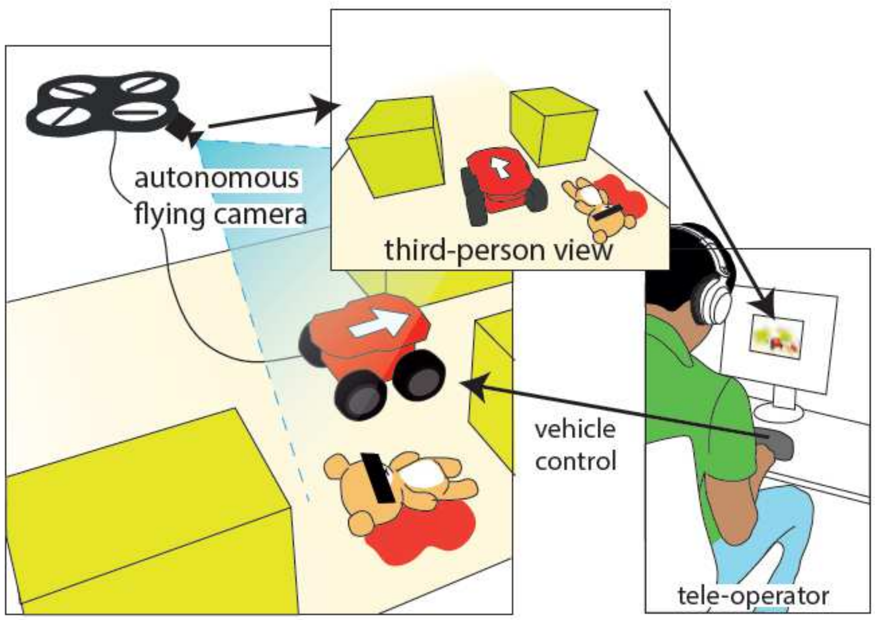

Figure 2-6Areal View That *(Saakes, Choudhary, Sakamoto, Inami, & Igarashi, 2013)* **Believe Improves Teleoperation**

An interesting characteristic of this quantification strategy is that it allows for the formulation of almost any type of hypothesis testing that relates to performance of teleoperation or telepresence. Such is the case of (Vasilijevic, Nad, Miskovic, & Vukic, 2014), a study that sets out to see if perhaps a binaural signals can be used to guide a teleoperator. Here they focus on setting up a feedback interface that relies solely on binaural headphones that emit a pinging signal of an object that they wish the operator to follow. Later, when the results are computed, they compare how well the driver was able to follow the sound signal based on an optimal path. Their findings are that it is possible to follow an object using purely auditory signals and that this may be used to augment user perception of the remote environment.

From the previous examples, a general method can be seen where each study selects specific characteristics attributed to operator performance while utilizing the system. These characteristics, such as deviation from path, total time of completion or errors per task, work as a reference point of off which general system performance standard can be established. By doing this, the researchers indirectly determine how well the system performs on a global level and then conclude the validity of their initial hypothesis. In otherworld's, if they hypothesize that “trait A is better than B”, then they would subsequently need to complete tests that incorporate trait A and measure the appropriate metrics. Afterward, they would conduct the same experiments with trait B. Later, they would have to compare the results of the metrics and only then would they be able to determine if one trait outperformed another.

2.2.2 Telepresence

Up to now, we've seen that some studies try to quantify teleoperation by linking it to operator performance; however more direct links can be established through Situational Awareness. This being said, these methods tend to rely on subjective parameters such as questionnaires performed during or after the participants complete a task. Some commonly used methods that appear in literature are Situation Awareness

Global Assessment Technique (SAGAT), Temple Presence Inventory (TPI) or NASAs Task Load Index (TLX).

Each of these methods tries to quantify how immersed a user is in the experience displayed. In the case of SAGAT the researcher must carefully prepare a questionnaire that is believed to be able to describe how aware an operator is of events currently happening. The questionnaire should be drafted so that it can measure SA in at least 3 levels, these being: level 1, perception of data; level 2, comprehension of meaning; and level 3, projection of the near future. In (Endsley & Garland, 2000) the authors describe an example oriented towards remote operation of an aircraft and tries to validate SAGAT by subjecting operators to different user interface configurations, measuring SA for each.

Another method found in literature is the Temple Presence Inventory (TPI) (Lombard, Ditton, & Weinstein, 2009) though its use is slightly different. Not intended to measure SA, it is designed to be used as a measure of the amount of immersion a user is capable of achieving while viewing video streams. These researches make a difference between 6 dimensions of presence, though they admit that other studies may suggest higher dimensions. The authors believe that everything can be summed up into just: 1- presence of transportation, 2- presence of realism, 3- presence as immersion, 4- presence as social realism, 5- presence as a social actor as a medium and 6- presence as medium as social actor. They later explain that one can try and measure these dimensions in various ways, such as recording facial expressions of users or developing questionnaires. They determine that the simplest and most effective way is via surveying users and thus develop TPI. Subsequently, they describe how to develop a questionnaire capable of measuring all the dimensions specified and later validate their work.

Alternatively, in the late 80's, NASA developed a Task Load Index (TLX) that sets out to quantify how demanding a teleoperation task may be. This is by far the most common metric used when subjectively trying to determine how "hard" a remote operation task is. The method states that teleoperation workload can be characterized by six dimensions: Mental Demand, Physical Demand, Temporal Demand, Performance Effort and Frustration. With this in mind, a questionnaire is handed to the operator after completing the required task, and they are instructed to rate each dimension. An example of the NASA TLX questionnaire can be seen in APPENDIX B page 1.

In this thesis a questionnaire is developed with the intent of rescuing the operator's opinion of how demanding the tasks were and how well the system responded to their inputs. The NASA task load index is used along with a questionnaire designed specifically for this investigation. More information regarding this questionnaire is available in APPENDIX B.

2.3 Internet Based Time Delays

Heretofore, we've explored general definitions of teleoperation and telepresence. However, the main difficulty when implementing wireless teleoperations systems pertains to how information is sent from the operator side to the remote side. In this section a brief description of some communication strategies are discuses and a description of complications encountered in internet based teleoperation are detailed.

(Hokayem & Spong, 2006), a well-known survey in teleoperation, provides a helpful recount of teleoperation trends through time and current research focus; by skillfully explaining how different technologies and communication mediums have shaped modern teleoperation. They argue that the main points of interest in modern teleoperation, from a controls perspective, are bilateral control and time delays in communication; highlighting the fact that the main goals are how to maintain or improve system stability and transparency in telepresence.

At its simplest, the main task of bilateral control is to provide the user with haptic feedback in such a way that the operator can physically interact with the remote environment while the maintaining system stability. As one can imagine, if time delay in the system is significant the user may “feel” and react in accordance to erroneous stimuli that ultimately reduces stability in the teleported system. Hence this issue has attracted many researchers to propose several methods for handling this type of situations, like: wave variable, smith predictors and Supervisory control methods, among others (Cui, Tosunoglu, Roberts, Moore, & Repperger, 2003).

The main cause behind time delay in teleoperation is centered on the inherent difficulties of how information is sent through the internet in wireless connections (Hokayem & Spong, 2006), i.e. packet switched networks. In essence, packet switching is the grouping of data into packets of bytes that are routed through a network so that the communication medium is only occupied while transferring the content of the packet. This data transfer method is most commonly used when communicating between computers over the internet and provides both advantages and disadvantages when compared to circuit switched networks. The main advantage is that the communications channel is only used while transferring packets, thus freeing it up to be able to connect more devices, but its drawback is that the amount of time that a packet may take to reach its destination is not known and will vary depending on when the packet is sent and the rout that is individually selected for each packet.

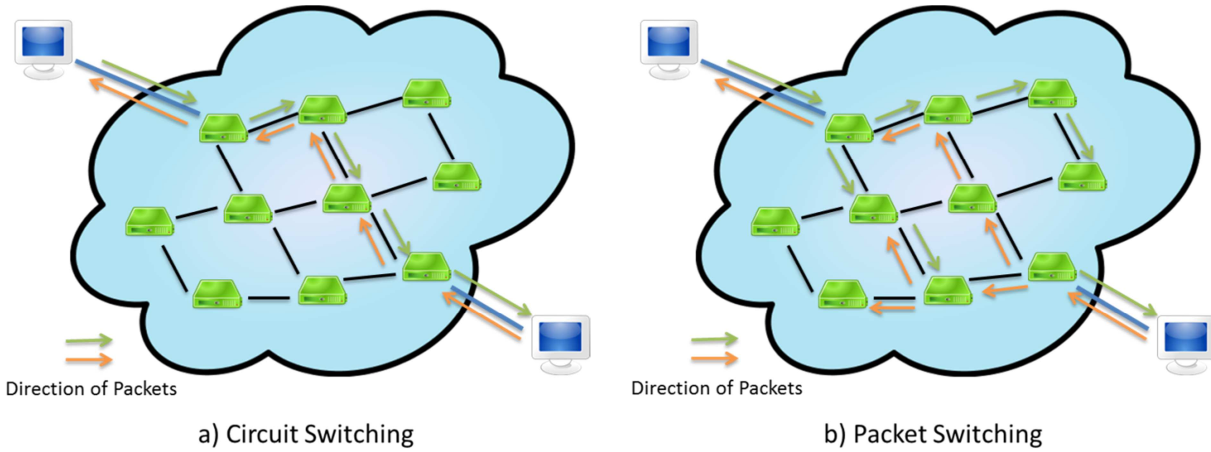

Figure 2-7 a) Circuit Switch Network. b) Packet Switch Network

Packet switching can be classified into two modes of sending information, 1- connectionless packet switching and 2- connection-oriented packets. In connectionless packet switching, each packet is addressed according to a selected protocol and subsequently sent into the network; this normally leads to each packet following different paths in the net and commonly results in out-of-order delivery. This in hand causes latency variance and, when applied to teleoperation, can ultimately lead to an unstable system. On the flip side, in general, the protocols that utilize this data transmission method tend to be much quicker than connection-oriented schemes and thus tend to be the preferred method for data transfer in streaming or general data transfer over the internet. One of the most common connectionless protocols is User Datagram Protocol or UDP, Figure 2-8.

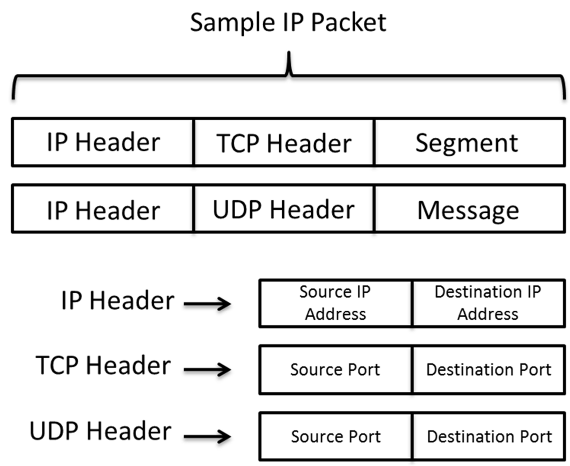

Figure 2-8 Sample IP Packet *(Northrup, 2016)*

In contrast, connection-oriented packet switching is a method that tries to guarantee the delivery and order of the packets sent. It accomplishes this by adding extra information to the header that provides a sequence number. This way, it can reconstruct the information in the appropriate order once it is received at the addressed computer. The extra information attached to each packet added to the reconstruction at the client computer adds further delay and, though quality is improved, the overall system latency is increased. The most common method for transmitting information like this is Transmission Control Protocol or TCP.

TCP Segment Header Format

Bit #	0 – 7	8 – 15	16 – 23	24 – 31
0	Source Port		Destination Port	
32	Sequence Number			
64	Acknowledgment Number			
96	Data Offset | Res	Flags	Window Size	
128	Header and Data Checksum		Urgent Pointer	
160...	Options			

UDP Datagram Header Format

Bit #	0 – 7	8 – 15	16 – 23	24 – 31
0	Source Port		Destination Port	
32	Length		Header and Data Checksum	

Figure 2-9 TCP and UDP Packet Headers *(Microchip Techonology Inc., 2016)*

Descending a few steps closer to the physical layer of the OSI classification of computer communications (International Organization for Standardization, 1996), different protocols that dictate how information should be parceled and subsequently transmitted over the physical layer exist. The physical layer is understood as the wireless medium used for connecting two or more users. The most commonly encountered technologies are Wi-Fi 802.11n, Bluetooth, 4G LTE and Dedicated Short Range Communications (DSRC). Each of the previous has unique advantages or disadvantages depending on the goals to be accomplished. For example, DSRC tends to have lower data rate throughputs, but significantly lower latencies, longer ranges and can be used at higher moving velocities (Harding, et al., 2014), therefore a general tendency exists to incorporate this medium into vehicles and hopefully improve safety. On the other hand, Bluetooth has lower data rates, but shorter distance and lower power consumptions; therefore they tend to be found in consumer mobile devices. Table 2-1 highlights principle characteristics of these different communications protocols.

Table 2-1 Wireless Technology Comparison *(Meier, 2005)*; *(IEEE, 2009)*; *(Zanchi, 2014)*; *(Rysavy Research, 2013)*

Type	**Throughput**	**Range**	**Bandwidth**	**Mean Latency**
Bluetooth	3 [Mbps]	50 [m]	2.4 [GHz]	25 [ms]
DSRC	54 [Mbps]	1000 [m]	5.9 [GHz]	2 [ms]
4G LTE	70 [Mbps]	>5000 [m]	700-2500 [MHz]	50 [ms]
Wi-Fi	600 [Mbps]	100 [m]	2.4 & 4.9 [GHz]	40 [ms]

In wireless teleoperations, the most commonly used medium is Wi-Fi due to the large throughput and versatility it offers (Swanson, 2013) (Hokayem & Spong, 2006). Nonetheless, other mediums, like Bluetooth, have still been studied in teleoperation with varying degrees of success, such as (Araque & Guerrero, 2010) and (Alshazly & Hassaballah, 2013).

However, though 4G LTE is not new, little studies exist that leverage this communications medium in teleoperation.

2.4 Current Applications of 4G LTE in Teleoperation

Cellular telecommunications has existed for several decades, allowing a large world to progressively become smaller and more mobile. Up until recently, data transfer rates were restrictively low for teleoperation, but as newer communications protocols have spawned, i.e. 3G and 4G LTE, a rise in opportunities for teleoperation have appeared recently in literature (Ericsson, 2015). Most cellular based investigations center their efforts in controlling automobiles in urban environments so as to provide support to an incoming wave of autonomous vehicles. This section will briefly detail some works that delve into cellular teleoperations and discuss advantages and drawbacks of their works.

One of the first appearances of a cellular teleoperations system, that this investigation reviewed, revolved around the control of a small robotic vehicle. Munoz (Munoz, Eusse, & Cruz, 2007) discussed the benefits of an eventual explosion in cellular connectivity and how this would enable a large boost in infrastructure for cellular connected devices. Because of this, they decided to configure a small test bed to determine the feasibility of teleoperating a vehicle over a cellular network. Some of their main concerns were data transfer rates and time delays in the system and thus centered their quantification strategy around gathering network variables that elucidated strains on the system. Furthermore, anticipating low data rates, they propose two control strategies; one being an autonomous system that resembled the supervisory-subordinate scheme, and a second more data intensive master-slave configuration. After constructing their system and conducting experiments to test their system, the authors come to the conclusion that though cellular teleoperation is possible, best results were achieved when using the supervisory-subordinate configuration due to latency (12.3 [s]) and low network transfer rates (1.1 [Kbps]).

More than 6 years later, (Gnatzig, Chucholowski, Tang, & Lienkamp, 2013) pick up where (Munoz, Eusse, & Cruz, 2007) left off by using 3G and 4G cellular networks to control a commercial vehicle over the internet. Here, the authors construct an internet based teleoperation system that connects through a cellular network. On the vehicle, appropriate modifications are made to the steering wheel and input modules so as to be able to control the vehicle “by wire”, and special attention is placed on safety by installing several redundancies to the brake pedals. Furthermore, the authors recognize that a weak link in the system is the video stream throughput and, though they have installed approximately 4 640x480 cameras, they implicitly state that they drive the vehicle streaming one or two cameras simultaneously at 320x240 resolutions. To test the system, they drive the vehicle in what appears to be a relatively straight line for approximate 200 [m] in a rural area at a constants speed preset into the cruise control. To quantify how well the teleoperator control the vehicle, they measure the offset of the drivers respect to an ideal path and how often the drivers tend to steer the wheel, with average calculated values of 0.4 [m] and 0.25 [Hz] respectively. In this papers discussion, the authors state that they successfully operated a vehicle through a cellular connection but imply that network difficulties play an important role in overall system performance and believe that autonomous control algorithms should be implemented in case connection is lost.

Most recently, (Shen, et al., 2016) also built a teleoperation system around different wireless mediums, including 4G cellular networks. Here, the authors retrofit a commercial vehicle so that it can to be controlled remotely, all the while using “off the shelf” products and implementing stereoscopic vision. In the paper, attention is emphasized on achieving low cost teleoperation of commercial automobiles so as to support autonomous vehicles in difficult situations in urban locations. In order to demonstrate that they can effectively control the vehicle, they make use of a large parking lot and have the operator perform slalom maneuvers around cones set on the ground. A test is considered successful if the operator is able to complete the course without skipping any of the cones. On top of this, they also measure success by comparing network variables, such as data transfer rates and latency, to Wi-Fi. This study concludes that teleoperation is viable and argue that low cost systems are readily available. However, they do warn that certain issues like connectivity, range to a cellular tower and speed of the vehicle may influence optimal teleoperations via cellular networks.

2.5 Summary

The intent of this chapter was to introduce basic concepts of teleoperated systems to the reader so that the following chapters can be understood easily. Different teleoperation architectures are introduced, like: Master-Slave, Supervisory-Subordinate, Partner-Partner, Teacher-Learner and Fully Autonomous. Industrial applications of teleoperation are detailed, such as: space applications, military applications, removing humans from hazardous environments encountered in mines or forestry and performing medical services at a distance like surgery.

The need for measuring teleoperation is discussed and common measuring strategies are described, such as time and frequency domain analysis. However, a more holistic approach is preferred and some examples are shown of investigations that derive how well a teleoperation system operates by analyzing operator performance using quantifiable metrics like total time to complete an experiment, the amount of error in the executing of a task or deviation from the ideal path.

Lastly, Inherent difficulties in internet based communications due to packet switching are explained and its effects on time delay in teleoperation are detailed. Furthermore, studies that delve into cellular based teleoperation are detailed and the strengths and weaknesses are described, such as: metrics used to infer performance, types of experiments completed and how success is measured.

CHAPTER 3

SYSTEM DESCRIPTION

When seeking to implement a teleoperated system, a plethora of options exist that depend on what objectives need to be accomplished. This case is no different and clear goals must be established in order to optimally design the teleoperation system. This studies main hypothesis is “a vehicle can be controlled over a 4G LTE network streaming HD video feedback”; all the while trying to maintain flexibility, where flexibility is understood as being able to easily use the system in deferent locations without requiring high initialization setups, such as installing specialized programs or purchasing expensive hardware.

Other constraints that further guide design efforts are: to use low cost and commercially available instruments, reducing the overall cost of implementation of any future teleoperation system; the main source of feedback must be video, eliminating the use of SLAM, LIDAR point cloud reconstructions on the operator environment or optical flow analysis of the video stream that might reduce the overall data stream of video feedback. Furthermore, the cameras must also be commercially available and compatible with real-time streaming. The Modems that connect to the cell towers must be commercially available 4G LTE modems along with commercially available data plans from any cellular network provider, and any data plan that is purchased cannot have preferential treatment when connecting to the cellular network or being assigned bandwidth.

Also, due to the inherit dangers of remotely operating a large vehicle (Swanson, 2013) it was decided a full sized automobile would not be used. However, with the intent of replicating the interactions present while driving, a golf cart is selected as the remote vehicle, thus simplifying safety management.

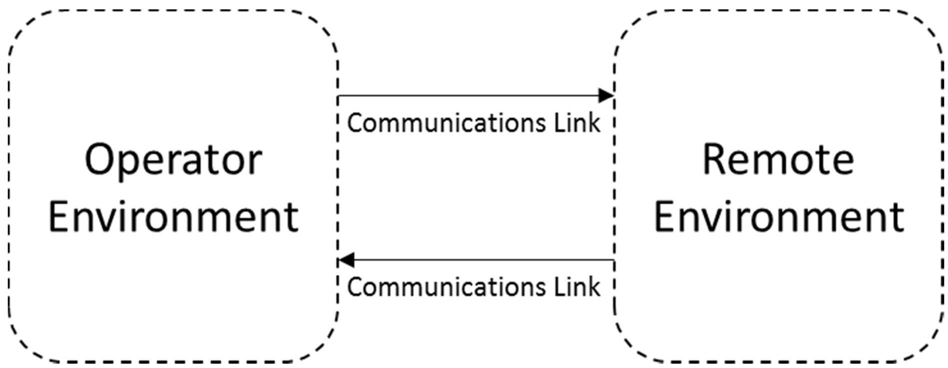

Figure 3-1 General Teleoperations Configuration

Understanding the primary objective and vehicle size constraint established, a brief summary of system alternatives will be discussed and the actual system will be detailed.

Several configurations exist when designing a teleoperation system, all linked by a general design that requires an Operator – Remote Environment connected through a communications medium, as seen in Figure 3-1. This studies primary objective is to use a 4G LTE communications protocol to relay information between each actor in the system, but this type of communications protocol inherently introduces complications that must be addressed with proper design methods and considerations. Therefore, as seen in CHAPTER 2, the teleoperation system will be implemented following the Master-Slave configuration while incorporating safety protocols from the Supervisory-Subordinate system.

The following chapter is divided in to three sub sections that analyze the system and better detail how it all integrates together. The subsections are divided into:

- The General Teleoperations Platform section, which determined the systems architecture and what programs are used in order to achieve teleoperation.
- The section Remote Vehicle System, describes the control architecture and provides further insight into how the remote system in built.
- The section Local Operator Station, details how information is captured and what the operator will be exposed to while driving the teleoperation system.

3.1 General Teleoperations Platform

Several alternatives to building a teleoperations system exist. Most cases determine which system is to be used based on the investigations overall objectives. In one example, as seen in (Marin, Sanz, & Sanches, 2002), the researcher's main interest is to propose a control system that can manipulate a robotic arm in a web based environment; thus the authors decide to build their system on a Java, Java3D and Cobra platform. (Vozar & Tilbury, 2014), seek to emulate latency filled teleoperation, for this they used Java programing language along with robotics specific libraries such as April Robotics Toolkit (APRIL) and Lightweight Communications and Marshaling (LCM) in order to simulate a remote environment and control time delays in the artificial communications link. Yet another system, and arguably one of the more popular alternatives, as described by (Swanson, 2013), is using Robot Operating System (ROS). This program is based off of Linux and has a large community that continually writes new libraries on diverse robotics subjects while simultaneously troubleshooting common issues.

Though all these options provide unique advantages when compared amongst each other, it is important to factor in the particular difficulties of teleoperation when the communications link is based on cellular networks. Taking this into consideration, a platform should be selected that minimizes these risks while complying with this studies main objectives.

At its most basic, the teleoperation system could be illustrated as in Figure 3-2.

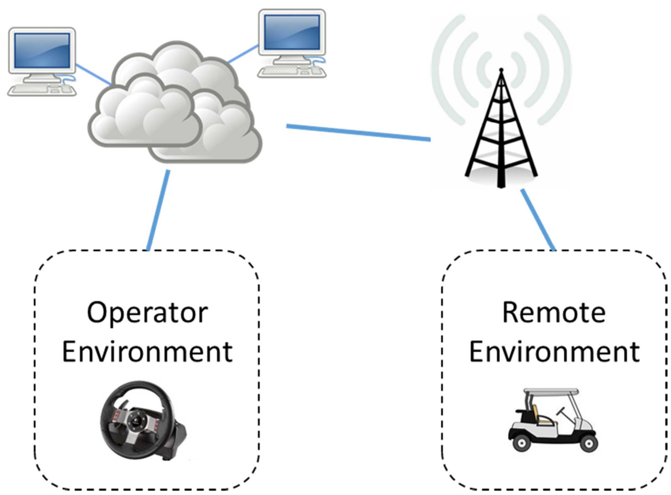

Figure 3-2 Cellular Network Teleoperation Scheme

The image shows how the information travels through the network crossing different nodes, be it cell towers or internet service provider nodes, and ultimately arrives at the operator station. Specifically, information captured on the remote vehicle is sent via the communications link to the nearest cellular tower. The tower in turn, transfers the information through the internet to the destination computer that, in this case, is located on the Georgia Tech Network. Despite only 4 nodes being illustrated: remote environment, cell tower, ISP nodes, and operator environment, these are not necessarily the total amount of nodes that the data will be relayed through, where the actual number may be much greater.

Furthermore, here the main obstacle is not the amount of nodes, but rather if the information passes through nodes that belong to different networks. This is important, because as the information approaches its destination, it may pass through firewalls. If so, special permissions may be needed or different interconnection strategies required. And, as expected, when entering the Georgia Tech network, the information must pass through a firewall.

Fortunately there are methods that allow for incoming information to pass the firewall, but these require certain considerations to be in place when designing the overall system. Without delving deeper into this specifics of the issue, a common method for sidestepping firewalls is to use “Session Traversal Utilities for NAT” (STUN) or “Transversal Using Relay around NAT” (TURN) servers, (Dutton, 2013). Here one makes use of a server that resides out of the destination network that allows for relaying information through firewalls.

Several methods exist that can achieve this, but luckily a few companies already exist that facilitate access to STUN/TURN server. One of these companies is Tokbox, an enterprise that is built around webRTC, an open source real time communications API, which enables browser to browser communications using video chat and messaging sessions, without the need of specialized software.

Given the fact that the primary goal is to be able to transmit information through a 4G LTE network that requires the use of STUN/TURN servers, and the company Tokbox that provides this service that incidentally is built around open source video conferencing software. This group decided to take advantage of the overlap, and build the system as a web app that uses web browsers as a platform.

Furthermore, the secondary objective of facilitating flexibility is achieved by building the system based on a browser environment, which is possible due to the fact that the TokBox is built around webRTC. Thus, by using web apps the platform leverages system flexibility, because virtually all computer that have internet access use web browsers, maintaining prerequisites for the system as low as possible.

On top of this, it was decided to keep to one programing language as much as possible. With this in mind, and since system would be web based, JavaScript was chosen as the primary reference language. Consequently, node JS, a JavaScript interpreter, is used to host a server and control interactions on the remote vehicle.

Having elaborated on the causes for selecting this teleoperation system architecture, Figure 3-3 details the resulting configuration of the system. Here, one can distinguish the categories previously described and how they interconnect given the current constraints.

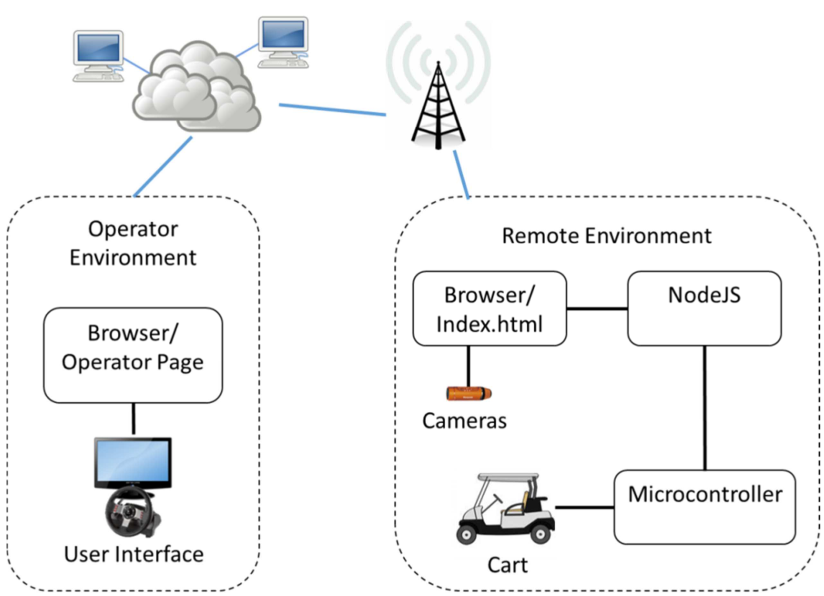

Figure 3-3 Teleoperation System Architecture

The Remote Environment and the Operator Environment represent the nodes that this study can directly control. Where the other nodes, cell towers and internet are considered black boxes and no influence exists over them. The operator environment represents the main interface of the system with the driver, and is where all the control signals are generated. While the remote environment is the actual vehicle to be controlled and where the feedback signals are generated and sent back to the operator station.

Generally speaking, two actions must occur for the system to be activated and allow teleoperation of the remote vehicle:

1. The remote vehicle must launch a server which initiates the communications session and,
2. The operator must start the user interface and open the operator web page establishing contact with the communications session on the vehicle.

In the continuing sections further detail as to what each subsystem does, shall be provided.

3.2 Remote Vehicle System

Using Figure 3-3 as a guide, the teleoperations system is initialized on the remote side by prompting node JS to create a server. This server in turn establishes a communications link between the remote vehicle and the operator station; and simultaneously monitors the vehicles microcontroller. The main objective of establishing a communications link is to relay control information from the operator station to the vehicle and at the same time transmit feedback to the driver so that he/she can control the automobile in real-time.

To better understand how the remote vehicle is controlled, it helps to visualize how information flows through the system, as seen in Figure 3-4. Here, the incoming information is every signal that the operator sends and that generates change in the remote vehicle, while all the outgoing signals represent the feedback that the driver requires to be able to reconstruct the remote environment and take appropriate action. Though the following representation of the system is slightly different to how it has been shown previously, this illustration allows for better identification of information flows and control nodes in the system.

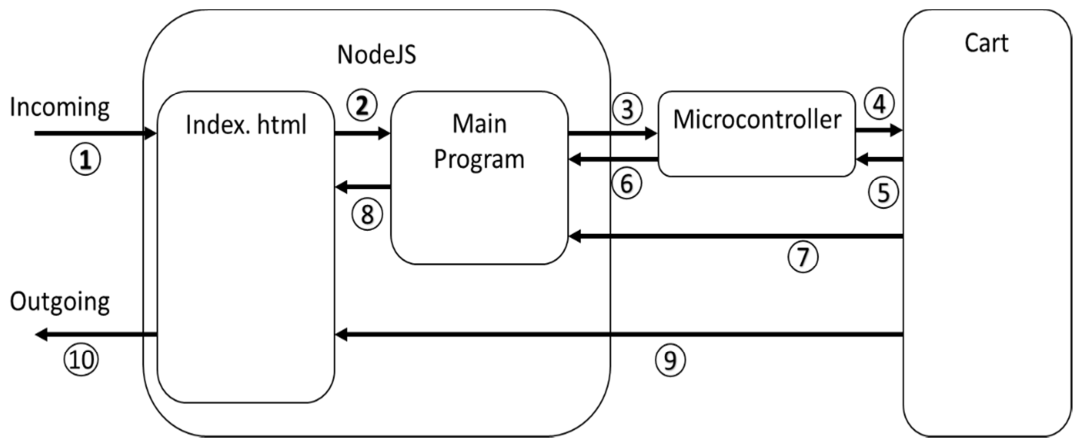

Figure 3-4 Remote Vehicle Control Nodes and Information Flow

Using the previous figure as a guide, more detail is provided as to what information is present in each stream line. A brief description regarding what data is being transmitted and why, as well as data transformations in the program blocks are detailed herein. Further description of the system is available in APPENDIX A.

- **Remote vehicle information flow**:
  - **Incoming Signals, line 1**: This line represents all the information that is captured on the remote vehicle coming from the operator station. It contains

all the data necessary to maneuver the steering wheel while providing more or less thrust and ancillary control signals for triggering camera views or other supplementary functions.

- **NodeJS-cart, lines 3 & 4**: Once the information is received and processed in the main program, this is in turn parsed and sent to the microcontroller on the vehicle or motor drive, so as to manipulate the remote environment.
- **Cart-NodeJS, lines 5, 6, 7 & 9**: As the cart is being feed control information from the main program, it too is sending information back regarding how the environment is changing. In particular, the vehicle is equipment with cameras, a LIDAR and other sensors that help the operator understand what changes are taking place on the remote vehicle.
- **Outgoing, line 10**: Finally, all the information is sent back to the operating station so that the operator can decipher the information and take appropriate steps to guarantee smooth and safe control of the vehicle.

- **Remote Vehicle Control Nodes**:
  - **Node JS**: the nodeJS interpreter contains the main program and the index.html file. The Index.html file acts as the interface to all of the incoming and outgoing signals that the cart receives. The main program is tasked with interpreting, scaling and transferring the signals to the microcontroller through the corresponding physical ports on the computer. On top of this, the main program aggregates external sensor information and implements safety measure as required.
  - **Microcontroller**: the microcontroller receives the translated control signals form the main program and converts them in to signals that the different elements within the system understand.

- **Cart**: the cart in the main body that is being controlled. It responds to the control signals sent from the microcontroller and simultaneously provides feedback to the main program by means of the various sensors that it houses. The sensor that are available on the cart are, a hall effect sensor for measuring wheel displacement, LIDAR for detecting objects in close proximity, a gyroscope and HD video cameras.

An important component of the remote system is the actual vehicle to be controlled. The golf cart houses all of the importation components that permit the system to relay information from and to the operator. Figure 3-6 details that specific location where the components are placed and a brief description is provided of each component.

Figure 3-5 Remote Vehicle – Golf Cart

Figure 3-6 Remote Vehicle System Break down

1. **Computer, item 1:** The computer is the main interface to all systems onboard the remote vehicle. I connects all sensors cameras that provide video feedback (4a and 4b). It communicates with the microcontroller that translates all signals to and from the vehicle. And provides the communications link to a local cellular tower through a 4G LTE modem. Furthermore, it also runs the programs and control logics previously described.

2. **Controller, item 2**: The Controller is composed of 2 main sub categories: the first a micro controller that translates signals sent form the Computer and the second the vehicle specific controller. In this case, this project uses the microcontroller to emulate voltages between the acceleration and brake encoders and the vehicle controller. By means of a pulse width modulation (PWM) signal, the controller is made to think that the encoders are being actioned and consequently it takes action by signaling the carts

main engine. The microcontroller also translates signals from the computer to the stepper motor drive. It receives the required angle position from the computer, calculates the steps the steering motor needs to reach said position and signals the drive to take the appropriate action. Furthermore, the microcontroller relays information from auxiliary sensors to the main program in the computer. The sensors that are captured are the Hall Effect sensor for measuring wheel displacement, LIDAR for detecting objects in close proximity and a gyroscope for detecting the vehicles angular velocity for post processing.

3. **Steering motor and drive, item 3:** The Steering motor and Drive act over the golf carts steering wheel. As described, the required steering wheel position is sent from the microcontroller to the drive. Here, the stepper motor powered from the vehicles power source (48 VDC), gyrates the wheel until it reaches the desired positon.

4. **Camera and Feedback, items 4a-4b:** Finally, camera feedback is provide through 4 cameras located in the areas shown by items 4a and 4b. Two possible locations are used for video feedback, these being the front and back positions. An overwhelming amount of studies that test teleoperation system performance tend to position the cameras in the front of the vehicle where a clear field of view is provided. However, when driving a vehicle the operator is commonly located inside of the cart with visual feedback of onboard displays and current steering wheel position. In prior tests, this study found it helpful to position the camera on the inside of the vehicle due to the fact that one could also see where the wheel position was during driving test. Because of this, this study proposes a secondary hypothesis that the "camera position significantly influences teleoperator performance" which is tested and analyzed in Section 5.2.1 of CHAPTER 5.

3.3 Local Operator Station

As previously stated, the second step that must be completed to initialize the system is to open the operator page and establishes a communications link between the remote vehicle and the operator station. This station generates every control signal needed to properly control the remote vehicle and is setup to resemble a typical automobile cockpit including: a steering wheel, gas and brake pedals, a stick shift to signal forward and revers, along with three screens that provide a wide as possible field of view.

Using the same illustration method, one can visualize the incoming and outgoing information form the operator page. However, in Figure 3-7 the incoming information corresponds to the outgoing from the remote system, and analogously, the outgoing from the operator station is the incoming to the remote vehicle.

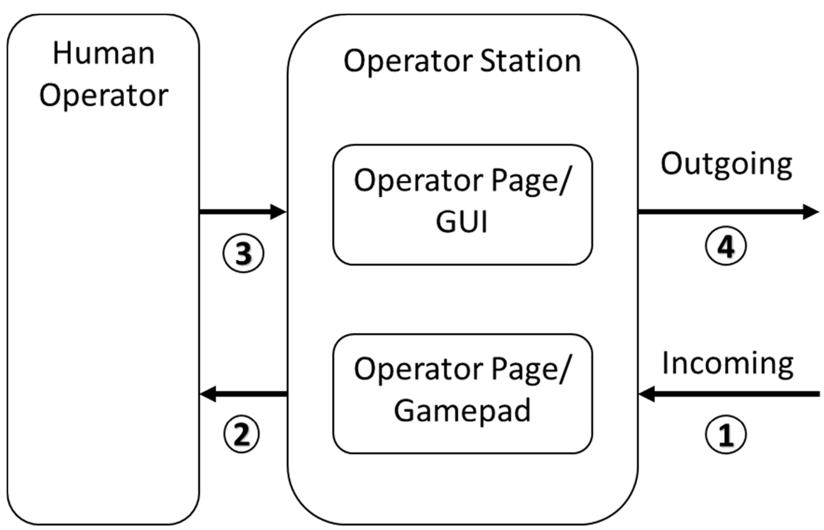

Figure 3-7 Local Operator Station Control Nodes and Information Flow

Though at first glance this system seems less intricate than the remote system, it is anything but that. The Operator Station combines several critical tasks into just three main nodes: operator station, gamepad and Graphics display. Moreover, it is tasked with relaying large amounts of information; all the control signals as well as all the video and auxiliary feedback. More detail as to of how the information is captured from the driver and subsequently displayed are described as well as the overall layout of the operator station. For further detail view APPENDIX A.

- **Operator Station information Flow**:
    - **Incoming, line 1**: The incoming information is mainly composed of the video stream session held by webRTC, and auxiliary feedback such as GPS position or LIDAR point cloud.
    - **Outgoing, line 4**: The outgoing data stream on the Operator side is the same as the incoming stream on the remote side.
- **Operator Station Nodes**:
    - **Operator station**: This principle node is manually started by the driver by accessing the operator web page through a browser and contains two processing programs: the Gamepad Node and the Graphics Display.
    - **Gamepad Node**: This node represents the direct interaction that the driver has with the operator station. Here, the user physically manipulates the gamepad which detects the control signals and sends them over the data session previously initiated. Figure 3-8 shows the setup used.

Figure 3-8 Gamepad Setup

- **Graphics display node**: The graphics display is show to the driver via three windows each on one of the three screens that the operator has. Each window controls one camera in the remote vehicle providing left, right, front and rear camera position views. The layout can be seen in Figure 3-9.

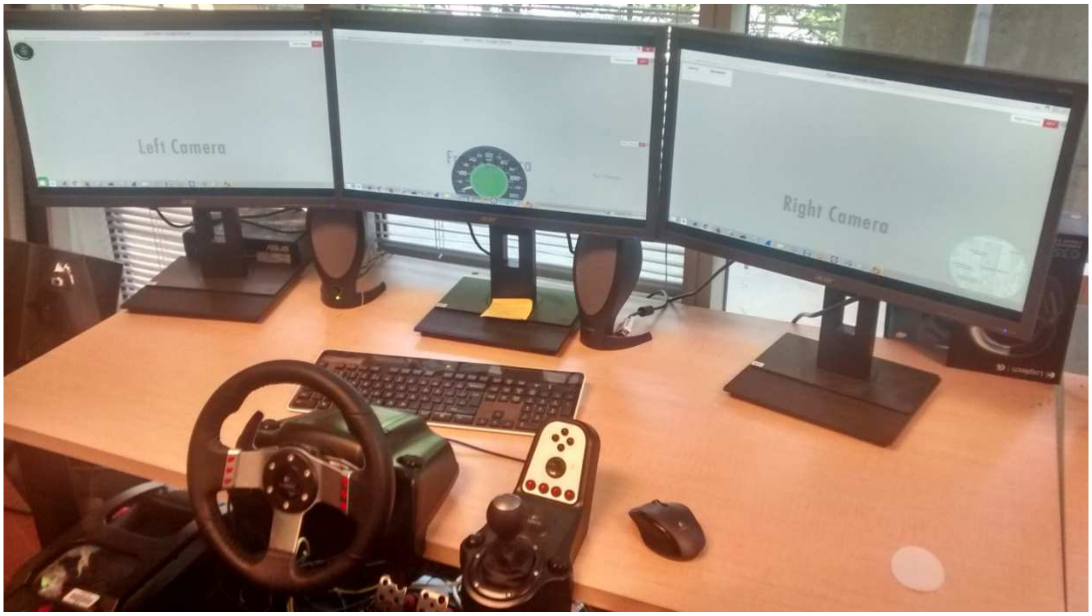

Figure 3-9 Graphics Display Setup

On top of providing the user with three screens for video feedback, he is also fed supplementary sensor feedback so as to enhance his situational awareness. The additional information is shown in terms of a prediction line, speedometer, a 2D LIDAR and a GPS map, as seen in Figure 3-9 and Figure 3-10.

- The prediction line is a visual overlay of the possible path that the vehicle will follow if the current settings are maintained. An example of this can be seen in Figure 3-10.
- The speedometer and 2D LIDAR are shown in the bottom center of the front view and provide the user two important control parameters that help the operator during task execution. While the main function of the speedometer is clearly detail the current speed of the vehicle, the 2D LIDAR's main object is to quantify the vehicles immediate surrounding taking the burden of guessing relative distances from a 2D image from the video stream. An example of this can be seen in Figure 3-9.

Figure 3-10 Visual Example of Prediction Line Overlay

3.4 Summary

Recapping this chapter, the general platform for teleoperations is presented. A comparison between common teleoperations systems is discussed and a browser based platform is chosen to be implemented; by weighing the benefits it provides over other system, i.e. network address translation though STUN/TURN. The general system architecture is presented and further detail is shown for both remote and operator stations. In the remote station different control nodes are detailed, explaining the fundamental roles each node completes. Likewise, in the operator station, control nodes are detailed and special considerations elaborated.

CHAPTER 4

EXPERIMENT DESIGN AND

STATISTICAL ANALYSIS

In order to properly confirm or reject any hypothesis, one must first devise a method of quantifying said statement and subsequently subject it to statistical analysis so as to determine its validity.

As discussed in previous chapters, several studies attempt to quantify teleoperation by controlling time delay and measuring its effect on the driving ability of the remote operator (Halme, Suomela, & Savela, 1999); while others try and model how an operator will react to local stimuli and determine what effects these have over system stability and control (Vozar & Tilbury, 2014) & (Swanson, 2013). Though these factors are important, they are not the focus of this work, whose intent is to determine whether “a vehicle can be controlled over a 4G LTE network streaming HD video feedback”.

With this in mind, this study attempts to indirectly asses the initial hypothesis’s validity by measuring operator performance while using the teleoperation system, and comparing it to performance commonly experienced while driving a vehicle locally. If the performance metrics are comparable, i.e. they share similar mean values, then it can be said that remote operators perform as well as in-situ drivers and consequently, the system allows for a vehicle to be controlled over the cellular network while streaming HD video feedback. Otherwise, two options exist: 1) the remote operator is able to perform better than expected or, 2) the teleoperator cannot control the vehicle to the proficiency levels required.

Herein, the reasoning behind how this study selects tasks that may capture the full particulars of driving are briefly discussed. Afterwards, a detailed description of the selected tasks and specific objectives for each are presented. Three main tasks are to be used for measuring performance, these being: 1) Straight Trajectory Tasks, 2) Reverse Trajectory Tasks, and 3) Path Following Tasks. Additionally, and as seen in CHAPTER 3, the camera position in the vehicle is not fixed and thus can be changed in between task. With this in mind, this study briefly describes how this may affect driver performance and details how this is varied in between tests.

Regarding data collection, a detailed list of variables to be acquired is presented along with the data logging strategy. Two different data acquisition methods are implemented in this study. The first leverages the asynchronous nature off of which the system is built and gathers information as an event is triggered. The second polls all relevant variables at a constant time interval and simultaneously logs them. Further detail is provided in Section 4.3 .

Certain variables, like vehicle position or time synchronization, require post-processing before being able to calculate the corresponding performance metric. The theoretical background and post-process algorithm are detailed in Section 4.4 .

Lastly, the statistical analysis plan used for determining the validity of the initial hypothesis is described. The actual analysis and interpretation of the results are presented in CHAPTER 5. Three main statistical tests are used for establishing whether the comparisons of the performance metrics are statistically significant. The test are: 1) the Kolmogorov-Smirnov Goodness of Fit test for determining normality, 2) depending on the previous, an F-test or Levene's test is used for comparing sample variances to the ground truths, and 3) a Two Sample T-test or a Kruskal-Wallis test is used for comparing the performance metrics mean to ground truths.

4.1 Tasks Selected for Measuring Performance

No unanimous consent exists regarding a metric that effectively reflects whether a remote driver is correctly performing the required tasks. Examples of this are shown in CHAPTER 2, where some studies performed tasks based on the author's discretion. Furthermore, objectives could vary wildly; where a subject would be required to cross an obstacle course, trace a figure 8 or simply follow a circular line.

With this in mind, this study looks at established entities whose objective is to quantify the ability of drivers and see if any parallels exist between them and this study that may be used for quantitatively measuring performance. From here, driving tasks are selected and specific completion criteria are described along with secondary objectives.

4.1.1 Origins of the Selected Tasks

In an attempt to use a standardized guide for measuring the operator's ability to teleoperate the system, and due to the intentional similarities that the system has with automobiles, this study uses a standard driver's license test as a guide for determining how well an operator can steer a vehicle. Though the Department of Motored Vehicles (DMV) tests vary depending on the state in which they are partaken, there are general guidelines that all test makers try to guarantee; as seen in the following list:

Minimum required skills for obtaining a driver's license (Georgia DDS, 2015).

1. **Parallel Parking**: Park midway between two standards so that your car is not more than 18 inches from the curb.

2. **Quick Stops**: Drive at a speed of 20 miles per hour and make a quick, safe stop when the examiner instructs you.

3. **Backing**: Back your car for a distance of about 50 feet, at a slow rate of speed, and as straight and as smoothly as possible. Turn your head and look back at all times while backing.

4. **Stopping for Signs or Traffic Signals**: Give the proper hand or brake signal; approach in the proper lane; stop before reaching a pedestrian crosswalk; and remain stopped until you can move safely through.

5. **Turnabout**: Turn your car in a narrow space using two-, three- or five- point turns.

6. **Use of Clutch**: If your car has a standard transmission, you must shift smoothly and correctly.

7. **Approaching Corners**: You must be in proper lane and look in both directions.

8. **Yielding Right-of-Way**: Always yield right-of-way to pedestrians, motor vehicles, bicyclists or anyone else who moves into the intersection before you.

9. **Turning**: Get into the proper lane and give signal an adequate distance before reaching the turn.

10. **Passing**: Always look ahead and behind to make sure you can safely pass without interfering with other traffic.

11. **Following**: Do not drive too closely behind other cars. Watch the car ahead of you; when it passes some reference point, such as a telephone pole, and then count "one-thousand-one, one-thousand-two." If you pass the same spot before you are through counting, you are following too closely.

12. **Posture**: Keep both hands on the steering wheel. Do not rest your elbow on the window and do not attempt to carry on a conversation with the Examiner because they will be busy giving instructions and recording your score.

Of the dozen of objectives previously listed, this research has chosen to focus on points, 2- Quick Stop, 3- Backing and 5- Turnabout; due to this studies ability to quantitatively measure the effectiveness of the driver's execution of the task. In other words, even though driver's license test administrators rely on personal opinion in determining whether a candidate has successfully preformed the given objective, the performance of the selected tasks are quantifiable and the logging of appropriate variables is readily available in the system.

Due to the fact that the objectives of this study do not completely match those described by DDS , the names of each of the selected tasks are changed. Furthermore, the new labels are used throughout the rest of this work. The updated tasks are named:

- Straight trajectory Task: formerly known as task 2- Quick stop.
- Reverse trajectory Task: formerly known as task 3- Backing.
- Path Following Task: formerly known as task 5- Turnabout.

4.1.2 Tasks and Description

Every task detailed herein rescues certain aspects that the DOT tries to qualitatively measure when testing prospective drivers. Many factors are involved in order for an operator to be able to accomplish each and every one of these objectives, such as understand how the environment is changing, perceive the vehicles relative velocity, estimate how much inertia the vehicle has and accurately measure depth perception, among others. Some of these tasks are already difficult for in-situ drivers, and the difficulty of these is compounded when taking into account how a teleoperation system degrades presence. This is why, though the tasks are based off of DOT metrics, certain parameters are modified in order to more accurately capture possible limitations the system has when acting as an intermediary between the operator and the remote location.

Considering all of this, specific details regrinding how the task will be completed, what path the operator must follow and secondary objects are described in the rest of this section.

4.1.2.1 Straight Trajectory tasks

The Straight Trajectory Task consists of driving the vehicle in a straight line and stopping on a checkpoint at the end of the run. Before beginning the test, the vehicle is properly positioned on the initial spot making sure that it is correctly directed towards the final location. Figure 4-1 shows the initial location that the vehicle will be positioned in, along with the ideal path the vehicle will be compared against for calculating performance.

In order to assure that each participant tries to accomplish the task under the same conditions, task specific constraints are detailed and conveyed to the operators. The objectives for the Straight Trajectory Tasks are:

- Drive as fast as comfortably possible.
- Maintain a speed as constant as possible throughout the whole task.
- Try to deviate a minimum from the path.
- Attempt to stop as close as possible, hopefully on top of, the checkpoint.

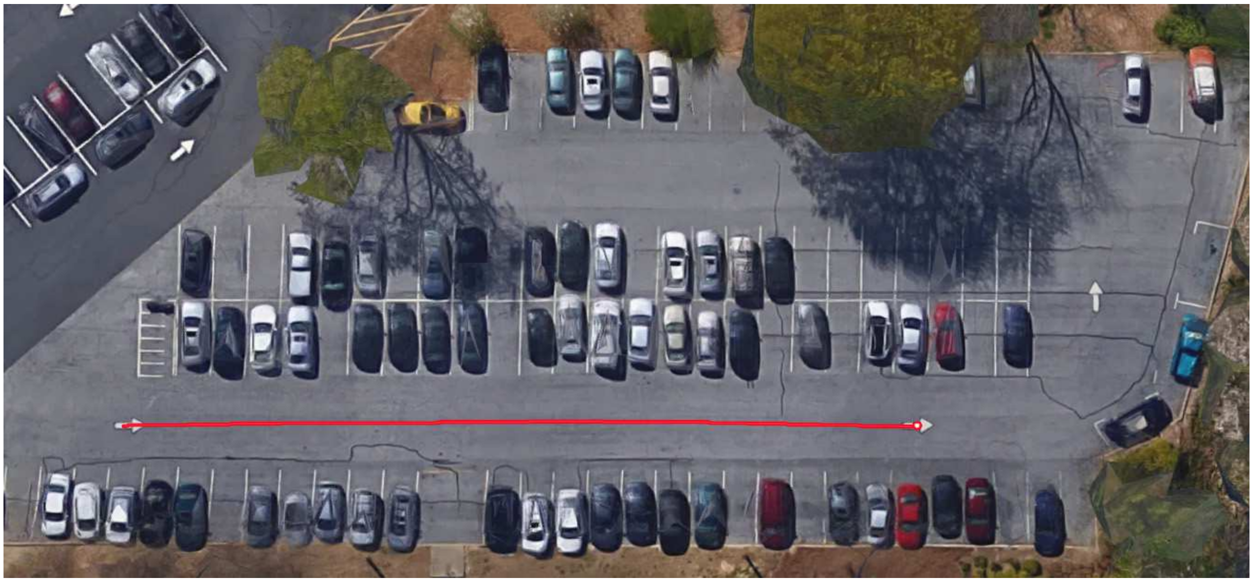

Figure 4-1 Straight Trajectory Task Overview

4.1.2.2 Reverse Trajectory Tasks

The second task that the participants will have to overcome is the Reverse Trajectory Task. This test offers a substantially larger degree of complexity due to the fact that the operators must control the vehicle while it is moving in reverse. Initially, the vehicle will be positioned on top of the starting checkpoint and oriented in the correct direction. From here, the operator will have to toggle the reverse position and drive the vehicle toward the first check point located in a delineated area half way through the whole course. When approaching the delineated area, the operator will have to maneuver so as to park the vehicle with the back end towards the sidewalk. Once the parking maneuver is completed, the operator will have to toggle the forward direction, pull out of the delineated area and head in the direction of the final check point. Lastly, the operator is asked, once more, to stop as close as possible to, or on top of, the checkpoint. Figure 4-2 shows where the task was completed and overlays the ideal path to which each run will be compared.

In an attempt to maintain clear task objectives and therefore reduce participant variabilities, task specific goals are again detailed and conveyed to the operators. The objectives for the Reverse Trajectory Tasks are:

- Maintain a speed as constant as possible.
- Maintain a speed that the operator feels comfortable with (not necessarily as fast as possible).
- Try to deviate a minimum from the path.
- Try and complete the task with the least amount of stops.
- Attempt to stop as close as possible, hopefully on top of, each checkpoint.

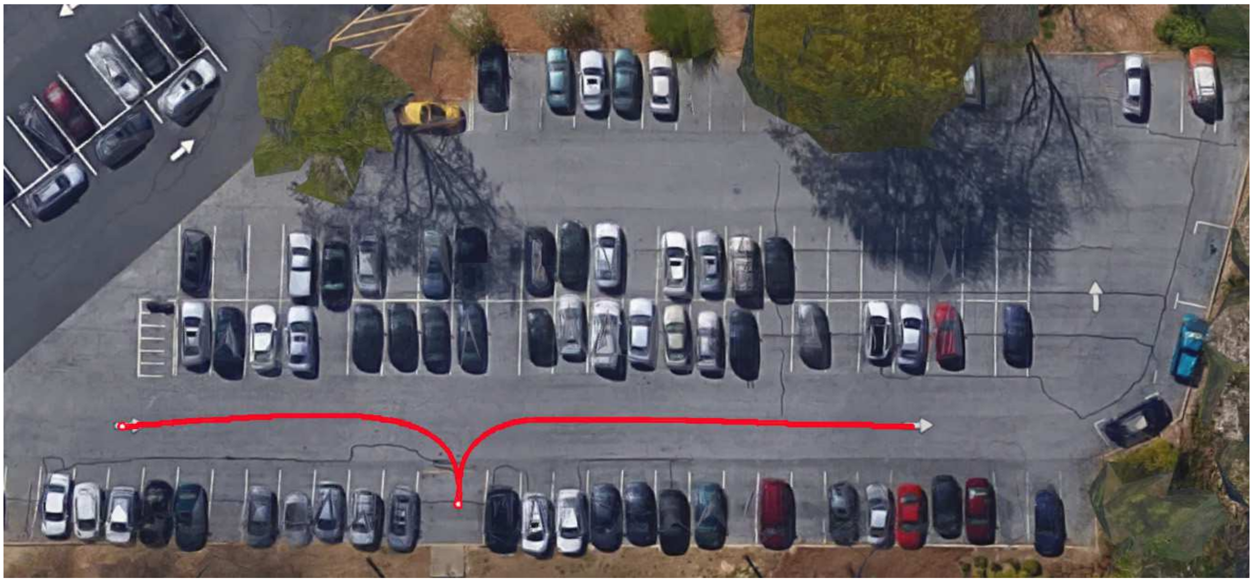

Figure 4-2 Reverse Trajectory Task Overview

4.1.2.3 Path Following Tasks

The final task that the operators have to complete is the Path Following Task. Again, this task presents significantly higher degree of complexity when compared to the previous task due to the fact that the operator has to steer the vehicle in 180 degree curves along with forward and reverse parking.

Before starting the task, the vehicle is prepositioned in the correct location and orientation. Once the participants are ready, they must first toggle the forward direction in the vehicle and subsequently start the test. Here they have to follow a straight path until they pass over the first checkpoint, after which they must immediately turn to the left. After completing a 180 degree turn to the left while passing over the second checkpoint, the participant must count 4 parking spots and stop his vehicle in the designated parking area. After this, they must toggle reverse and back out in a straight line so as to park in the parking area immediately behind their previous location. After completing the second parking maneuver, they must again toggle forward and pull out of the parking area while simultaneously turning to the left, in the direction of travel, so as to back track their previous path and go over the aforementioned checkpoints to ultimately stop on top of the final position. An illustration of the checkpoints and the maneuvers that the operator must complete is shown in Figure 4-3 along with the ideal path that they must follow.

Again, specific task objectives are detailed and conveyed to the operator so as to reduce unnecessary variances. The goals for the Path following task are:

- Maintain a speed as constant as possible.
- Maintain a speed that the operator feels comfortable with (not necessarily as fast as possible).
- Try to deviate a minimum from the path.
- Try and complete the task with the least amount of stops.
- Attempt to stop as close as possible, hopefully on top of each checkpoint.

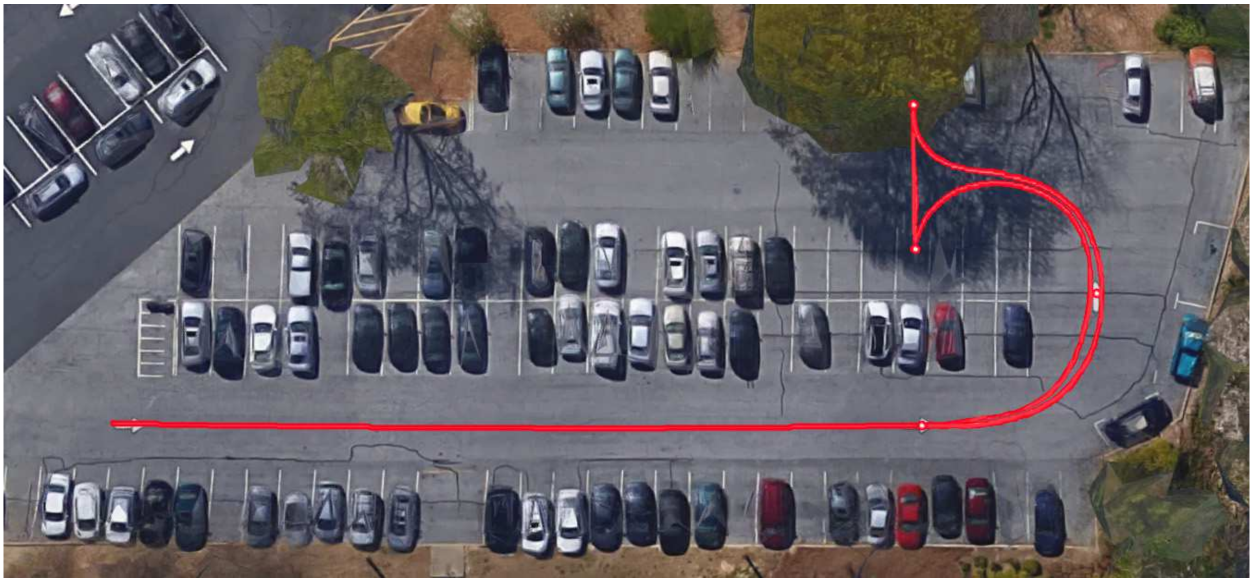

Figure 4-3 Path Following Task Overview

4.2 Telepresence and Camera Position

Measuring telepresence is difficult and authors tend to rely on subjective surveys performed during or after experiments, where the subjects Situational Awareness is measured in lieu of telepresence, by having each operator answer a questionnaire of carefully crafted questions. Moreover, even if one could determine a non-subjective way of measuring telepresence, it would be difficult to generalize the index, all this because telepresence is a function of several factors that try to understand how humans interpret remote environments.

Though an ideal outcome of further research in this area would be to develop a single index capable of quantifying how well the remote environment is being relayed to the user in function of telepresence parameters, it is not the current objective of this study. Nevertheless, this investigation has allowed for flexibility regarding perhaps the most important factor in telepresence, the camera position. Here, the system is built in such a way that it allows for the operators point of view to be modified so that his perspective can be placed inside the cockpit or on the outside. With this in mind, this section describes how said parameter is modified and what is expected when altering the point of view.

Furthermore, this study has developed a questionnaire that will be filled out by each participant after the completion of every task. Its intent is to provide broader perspectives when understanding the individual complication that that the users experience, thus providing an extra dimension to the analysis. For more detail regarding the questions that form part of the questionnaire, please refer to APPDENDIX B.

4.2.1 Camera Position Variability

As described in CHAPTER 3, the remote vehicle counts with 2 camera mounting locations: one in the front of the windshield pillars under the roof, and one behind the driver's seat close to the head level, as seen in Figure 3-6. These locations are chosen for two specific reasons:

1. An overwhelming amount of studies tend to position cameras in front of the vehicle or somewhere that the driver is not normally located. This forces the interface to shown a view that the drivers don't normally experience, which this study believes may force the operator to present reduced operational performance.
2. Secondly, this study believes that by placing the cameras in a location where the drivers head would normally be situated, will give the remote operator a more "natural" sense of the actual surroundings. Consequently, improving the operator's situational awareness and providing visual feedback of both the steering wheel reacting to the sent control signals and better depth perception between the vehicle and external interferences.

During the experiments, the operators will be subject to completing each of the aforementioned tasks under both camera position settings. That is, they will be required to complete each task with the cameras mounted in one of the previous configurations, and after having completed all the objectives, they will then be required to repeat each task with the cameras located in the alternative location. After collecting all the required information, the two tasks will be compared amongst each other in hopes of determining if there is any difference between the camera positions. With this, a secondary hypothesis is formulated, stating that "the camera positions have a significant effect on performance when teleoperating a vehicle". In order to validate said hypothesis, this study uses the same statistical analysis that is used for the principle hypothesis, as detailed in Section 0.

4.3 Variables logged and Data collection

In order to properly quantify performance and subsequently validate the primary hypothesis, relevant information has to be extracted from each of the previous tasks. Due to how our system is configured, several variables can be acquired during the executing of the tests using two different data logging methods. Herein, the variables to be collated are detailed and the acquisition strategies described.

4.3.1 Logged Variables

Each one of the previous tasks will be conducted under a controlled environment with the intent of logging several variables that can later be used to determine how well the system performed while being teleoperated. Due to how our system is configured, this study is capable of registering the following variables:

- Vehicle steering wheel position
- Vehicle gas pedal position

- Vehicle brake pedal position
- Distance traveled (position sensor on the wheel)
- Direction of travel (forward, reverse or neutral)
- Z-axis gyroscope
- Current camera angle position

Analogously, this study also logs the following operator side variables:

- Steering wheel position
- Gas pedal position
- Brake pedal position
- Direction of travel (forward, reverse or neutral)
- Current camera angle position

4.3.2 Data Logging Methods

Regrinding data acquisition, several different methods exist for logging and storing relevant information. Though it would seem better to individually register each action on operators station PC, two main factors steer this research into developing a different logging approach, these being; software system restrictions and event time synchronization. An Important reason for not logging actions on local computers is that the software off of which the system is built does not easily permit the host server to run scripts that modify the file system on the client machine. In other words, since the system is based on nodeJS and each client connects to the host server through a browser, writing to the clients file system is difficult and can lead to errors while logging events or afterwards when trying to collect and process the registered data.

The second, and arguably more important issue, is time synchronization. Since events are triggered on different computers and time stamps are calculated accessing the local computers reference clock, no assurance exists that both clocks are properly synchronized. Due to this, a recurrent function is periodically executed with the intention of logging the offset between clocks in both computers. For this, an NTP protocol was studied and implemented using assumptions commonly accepted for calculating network timing (Mills, 2014). More on how this protocol assesses the time difference is shown in Section 4.4.2 of this chapter.

With the previous limitations in mind, this study now explains how data is registered and the logging philosophy implemented. The current system uses two approaches towards logging, one being event driven and the other being time based. The fundamental reason for using two approaches are; event based logging provides more fluid representation of what is changing as it happens, while the time based method enables us to register every variables value periodically throughout the whole experiment.

4.3.2.1 Event Driven Data Logging

For the event driven data collection, the system leverages nodeJS's asynchronous properties to better determine the time at which an action takes place. Here an event listener is established, which continually checks to see if an action occurs. Once the event listener detects new information, it executes a specific program associated to the particular event. It is in this instance that the system is forced to record the information and keep track of when the event was triggered. Generally speaking, each variable used to control the remote vehicle will be modified and a small script of code will be inserted in order to allow for the logging of said variable.

4.3.2.2 Constant Time Interval Data logging

For the time based data acquisition method, the logging process is straight forward. This study simply adds a function to the general code that is executed at a constant rate, registering the global values of each variable and storing them in a file along with their corresponding time stamp. In other words, each variable is assigned a global memory slot that reaches across the whole program. As the program runs and different events are triggered, the local variable copies its value to the global variable and thus provides a registry of the last available value. When a predetermined time passes, the logging function is executed and consequently each global variable is read and copied to the data storage file.

4.4 Variables Post-Processing

Though most variables collected during the execution of the tasks are ready for being interpreted as a performance metric, some require some processing before useful information can be extracted. The specific performance metrics that depend on post processing are the distance deviated from the path and the time delay in between sending and receiving control signals. The first metric depends on being able to determine the correct path that the vehicle completed over the task. While the second depends on properly synchronizing the two computer clocks and subsequently determining the moment when one signal is sent and hen the same signal is received.

4.4.1 Distance Variable processing

For determining the position of the vehicle a simplified bicycle model is developed using input variables collected in this study. In literature one typically encounters a dynamic bicycle model that determines the acceleration and yaw rate of the vehicle in function of lateral velocity and current yaw that the vehicle has, all this after having gathered vehicle specific constants. Unfortunately, due to the limited precision of the accelerometer used in this study and large vibrations present in the vehicle when starting, the following bicycle model is used to calculate the vehicle position (Sharma, 2014) . From Figure 4-4 and geometric correlations, equation 4-2 determines the vehicle's yaw rate in function of the steering angle and linear differential distance, captured from the steering motor encoder and position sensor on the vehicles wheel respectively. Similar to other commonly used bicycle models (Jazar, 2014) (Swanson, 2013), this model assumes that the steering angles are small and that the effect of slippage between tires and roads is negligible.

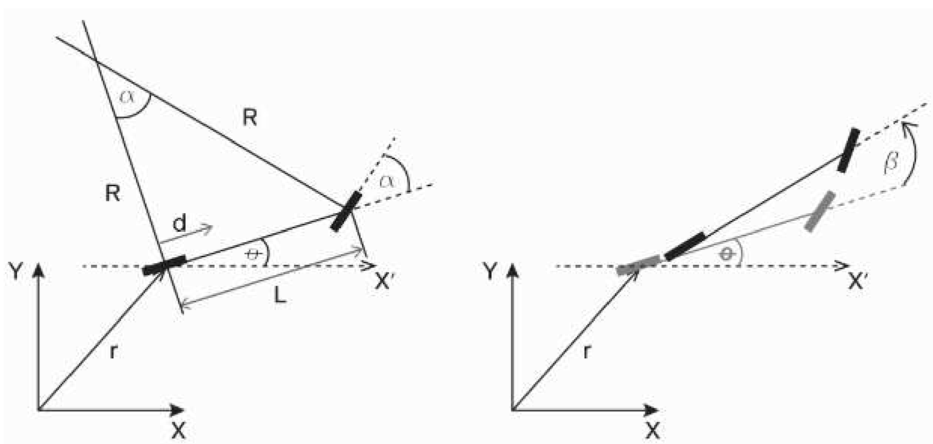

Figure 4-4 Bicycle Model Geometric Model

$$\tan\alpha = \frac{L}{R} \qquad \textit{eq. 4-1}$$

$$\beta = \frac{d}{R} = \frac{d}{L}\tan\alpha \qquad \textit{eq. 4-2}$$

On top of determining the yaw through the geometric bicycle model, the gyroscope provides the current instantaneous yaw rate that can be used to calculate a second yaw angle, as seen in equation 4-3.

$$\beta = \dot{\theta} \cdot \Delta t \qquad \textit{eq. 4-3}$$

Both of these values are filtered together using a Kalman filter (Welch, 2016) for a single variable and then used as inputs to the general equation of motion of the vehicle.

$$\begin{bmatrix} X_{f(t+1)} \\ Y_{f(t+1)} \\ X_{r(t+1)} \\ Y_{r(t+1)} \\ \theta_{t+1} \end{bmatrix} = \begin{bmatrix} \cos(\theta_t + \beta) & -\sin(\theta_t + \beta) & 0 & 0 \\ \sin(\theta_t + \beta) & \cos(\theta_t + \beta) & 0 & 0 \\ 0 & 0 & \cos(\theta_t + \beta) & 0 \\ 0 & 0 & 0 & \sin(\theta_t + \beta) \\ 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} L \\ 0 \\ d_t \\ d_t \\ \beta \end{bmatrix} + \begin{bmatrix} X_{r(t)} \\ Y_{r(t)} \\ X_{r(t)} \\ Y_{r(t)} \\ \theta_t \end{bmatrix} \qquad \textit{eq. 4-4}$$

4.4.2 Time Synchronization Algorithm

Regarding time synchronization of the computer clocks, an NTP algorithm is studied and incorporated in the system (Mills, 2014). Here, once the teleoperation system is initialized a recurring function sends out a signal to the operator station with a timestamp S1. When this event is received at the operator station, the time is logged with time stamp R1 and subsequently sent back to the remote vehicle with the sent timestamp S2. Finally, when it is received at the remote vehicle, timestamp R2 is logged and stored in the system memory. An illustration of the process is shown in Figure 4-5.

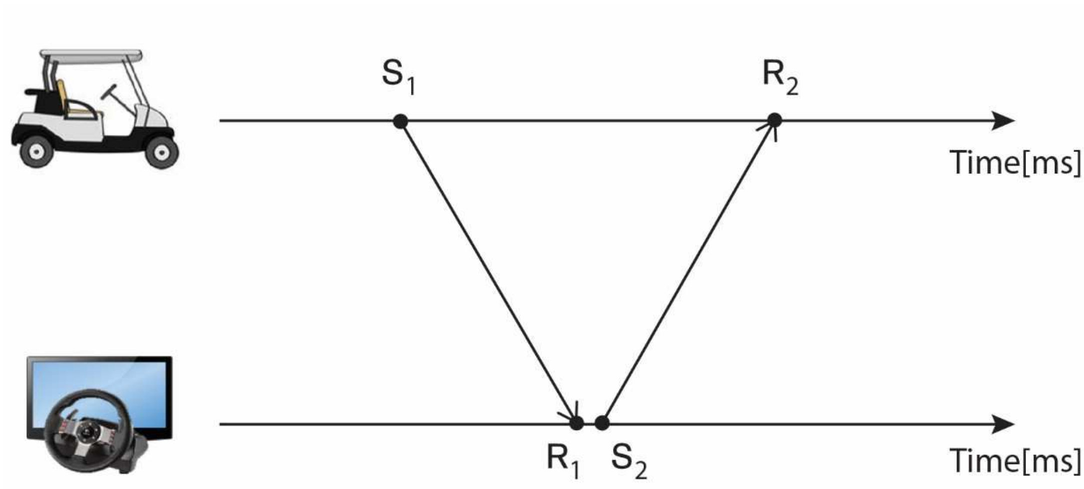

Figure 4-5 NTP Time Stamp Algorithm

After the tasks are completed and once processing of the information is started, time offset θ and round trip time δ metrics are calculated using equations 4-5 and4-6 respectively.

$$\theta = \frac{(R_1 - S_1) + (S_2 - R_2)}{2} \qquad \textit{eq. 4-5}$$

$$\delta = (R_2 - S_1) - (S_2 - R_1) \qquad \textit{eq. 4-6}$$

It is important to highlight that in this study latency is understood as the difference of time between when an input signal is captured by the operator station and when it is received on the remote environment. Some studies tend to define latency as the round trip time cause by an event, however this type of accounting of latency is very difficult due to the need of identifying when a stimulus is triggered on the remote environment and reliably capturing an associated timestamp (sometimes embedded in an image in the video stream). Later, one must then determine when the operator reacts to this stimulus and consequently manipulates the gamepad, which captures his response, accounting for “human latency”. Lastly, the input signal is then sent through the network where the remote system must actuate the environment accounting for the roundtrip latency of an event. Reiterating, this type of accounting of latency is not logged in this study.

4.5 Statistical Analysis

The previous work of: selecting appropriate tasks; determining how system variables are collected; and post processing, is done in order to be able to calculate performance metrics for the teleoperated system. However, this work is pointless unless some sort of comparison can be established that helps determine the validity of the initial hypothesis. To achieve this, ground truth test that establishes a point of comparison to each of the performance metrics are completed. These ground runs are completed taking into account the same objectives of each task, with the distinct difference that the driver is located in the vehicle as opposed to remotely. Once local driving performance is established and teleoperation performance metrics for each task are calculated, one can then compare the metrics via statistical analysis in order to determine whether or not they share similar means, and thus conclude the validity of the hypothesis.

The following statistical tests are selected in order to validate or reject the hypothesis “A vehicle can be controlled over a 4G LTE network streaming HD video feedback”. The significance level α of each test is set at 0.05 and the type II error β to 0.2. This entails that for the following analysis, the tests are able to reject the hypothesis for different means with a confidence interval of 95%. Furthermore, using a power of 80% (type II error of β equal to 0.2) and a mean differences effect size of 0.6 (Cohen, 1992), the sample size is calculated to be at least 20 for each performance metric. Thus, if the mean comparison statistical test rejects its null hypothesis then the validity of the studies initial hypothesis would be rejected. A three stage statistical test is design and detailed herein:

- Stage 1 - Kolmogorov-Smirnov test (KS-test). This nonparametric test determines if a sample comes from a normal distribution. The test is implemented by using the function “kstest” in Matlab to each metric in an attempt to determine whether they can be considered to have a normal distribution at a significance level of α equal to 5%. The test rejects the null hypothesis with a p-value under the significance level (α equal to 0.05).

  Because of the limited sample size used in this study and the difficulty of complying with a principle assumption of the Chi-Square test, the Kolmogorov-Smirnov test is preferred.

  This test sets a precedent for the following statistical tests. Based on whether the studied distribution is deemed normal or not, the following stages will select the more appropriate statistical tests. In other words, if the KS-test deems that the distribution is normal, then it is preferred to use a parametric test which, tend to be more robust and deliver better predictions when used with known distributions. On the other hand, if the KS test cannot determine normality, then a less sensitive to non-normality or non-parametric test is preferred, delivering more robustness and better predictions for unspecified distributions.
- Stage 2 - Variance comparison. The second stage is used to determine whether the variances of the samples are similar at a significance level of 5%. Two

methods are used in measuring variance similarities: the first is the F-test and the second is the Levene test.

The F-test is implemented by calling "vartest2" function in Matlab. This test uses the F-distribution to determine the validity of the null hypothesis that "both samples come from normal distributions with the same variance". If the p-value falls under 0.05 then the hypothesis is rejected. This test is used if the null hypothesis in the first statistical test is not rejected, i.e. the performance metric follows a normal distribution. Thus a parametric test is preferred.

In the case that the performance metric does not follow a normal distribution, this study uses the Levene-test, a test less sensitive to non-normality, to check for similar variances. Here, the null hypothesis is similar to the F-test, but it is not as sensitive to samples that do not follow normal distribution. The null hypothesis is rejected with p-values under 0.05. It is implemented using the function "vartestn" in Matlab and setting the testing option to "LeveneAbsolute".

- Stage 3 - Mean comparison. After having completed the previous tests, each individual performance metrics can be compared to the ground truth and its validity determined. Here, this study uses one of two statistical tests, these being a Two Sample T-test or Kruskal-Wallis test. The Two sample T-test performs better for normally distributed samples whereas the Kruskal-Wallis is not as sensitive as the T-test to distributions that are not normal. Both share the hypothesis that "the samples come from independent distributions with equal means" and is rejected with p-values under 0.05. The same principle for parametric tests applies in this stage too. That is, the two-sample T-test, a parametric test, provides better predictions for data that follows a normal distribution, whereas the Kruskal-Wallis test, a non-parametric test, performs better under unspecified distributions.

4.6 Summary

In summary, three tasks are selected from a list of tests commonly used to measure driver qualification (Georgia DDS, 2015). The selected tasks are:

- Straight Trajectory Tasks,
- Reverse Trajectory Tasks, &
- Path Following Tasks.

On top of detailing the tasks that will be used for measuring operator performance in the teleoperated system, data logging methods and variables are detailed. Essentially, two methods will be used simultaneously for collecting data: event driven logging and time constant logging. Event driven logging takes advantage of nodeJS's asynchronous nature and provides precise time stamps for each event triggered in the system. While Time constant logging surveys each variable during each time step and simultaneously logs them.

Some performance metrics require more involved calculations before they are ready to measure performance. With this in mind, the theoretical background for the calculation of path based and time based metrics are described. Regarding the path based metrics; a simple bicycle model is used to determine the position of the vehicle in each time step. While for the time based metrics, a time synchronization scheme is implemented based on NTP.

Lastly a three stage statistical test is described used for determining the validity of the principle hypotheses:

- The first stage determines the normality of the logged performance metrics by the use of a nonparametric KS-test.

- The second stage compares the performance metrics variance to that of the ground truths by either using an F-test, parametric, or a Levene test, a test less to non-normality. If in the first stage, the metric is deemed to be normal, then an F-test is used; otherwise a Levene test is used.
- The third stage compares the performance metrics mean to the ground truth mean. This is done using either a two sample T-Test, parametric, or a Kruskal-Wallis test, non-parametric test. Again, if in the first stage the metric is deemed to be normal, then a two sample T-test is used; otherwise a Kruskal-Wallis test is conducted.

CHAPTER 5

RESULTS AND ANALYSIS

Herein the results of the data collection and processing are shown with the intent of determining the validity of the initial hypothesis; “A vehicle can be controlled over a 4G LTE network streaming HD video feedback”. Though this statement may seem open-ended, its validity can be inferred by the results of well bounded metrics that seek to quantify the performance of remote drivers. As seen in CHAPTER 2, little consensus exists as to what metric best predicts performance, thus several parameters were captured during experimentation, and resultant of this, various performance metrics are calculated and used as comparison, providing a more holistic view of how the operator performed. On top of this, ground truth runs that were previously logged are used as a frame of reference to help determine overall performance of the teleoperation system.

This chapter is divided into two main sections: results and analysis. In the first, the calculated metrics are listed and described so as to introduce the reader to the criteria that is used to measure performance. Subsequently, highlighted results are detailed and the statistical analysis shown in CHAPTER 4 is applied to the results in order to determine how the teleoperation system allowed the operators to perform. After, the questionnaire results are presented and discussed, providing qualitative insight to what the participants experienced and what they believe hindered their performance.

The second section delves into understanding the possible reasons for the performance seen. Initially, the camera location is studied by comparing the performance metrics and their means through the statistical analysis. Since it is determined that this factor does not likely cause systems difficulties, a deeper look into how latency varies is carry out.

Two main comparisons are studied regarding latency. In the first, latency is compared to several performance metrics in order to see if any patterns emerge that may warrant further research. Secondly, the latency profiles are compared to the vehicle parameters collected during each experiment by overlaying them in function of time. From these analysis, possible causes for the systems underperformance are hypothesizes for future work.

5.1 Results

5.1.1 Performance Metrics

During the data collection stage, 20 participants completed the tasks described in CHAPTER 4. Before teleoperation, each subject was driven through each test in the exact location that they would later remotely drive the vehicle. Furthermore, before starting the tests, they were allotted 5 minutes of free drive time to get accustomed to the latency and feel of system. Subsequently, they were instructed to complete each test to the best of their abilities. During each task, a team member was permanently stationed on the vehicle, capturing the data and ensuring safety. The “copilot” could halt the task at any given moment if he foresaw possible unsafe conditions. In total, a little under 5 hours of drive time were logged and the emergency stop was activated 6 times. Though the stop was activated, the option of finishing the task was given to each subject, to which every driver accepted and ultimately completed the test.

From the variables collected during teleoperation three main category of performance metrics are established: trajectory performance, control signal performance and system variables performance. Each of these categories has parameters that are calculated from different sources attempting to characterize how the subject drove during the test.

5.1.1.1 Trajectory Performance Metrics

The first category, trajectory performance, uses the logged data to calculate the trajectory that the vehicle follows and determines performance metrics by comparing the subject's trajectory to an ideal path. A visual representation of the computed metrics can be seen in Figure 5-1. The computed metrics are:

- The Maximum Deviation from Path [m], measures how far the center of the vehicle diverged from the ideal path over which it should be on. This metric provides an extremes comparison to performance since it only returns the largest distance that the vehicle deviated by. It is obtained by calculating the perpendicular distance from the vehicle onto the ideal path. (this is shown as dark red in Figure 5-1)
- The Distance from Checkpoints [m] metric is the same as the previous, the difference being that it only takes into account a specific point on the ideal path. (Distance from the path (blue line) to the red circles).
- The Length of Run [m] metric details the total distance traveled by the vehicle. It provides longitudinal perspective on how closely the vehicle was able to stick to the track. It is calculated by summing the differential displacement of each point.
- The Area of Deviation [m^2] in function of Position, commonly referred to in this work as just Area, takes into account the total distance deviation over the whole task. This metric provides an extra dimension of information of how the task was executed. It is calculated by determining the perpendicular distance of each point

to the ideal path and multiplying it by the differential distance taken in each corresponding step. (this is represented by the light blue area in Figure 5-1)

- The Area of Deviation in function of Time [-] provides yet another degree of information to the area deviation metric. This metric not only calculates the area that the vehicle deviates from the ideal path but additionally weights the differential area with the time that the vehicle was away from its path.
- The Ratio Area Deviated over Distance Traveled [-] normalizes the Area metric in function of the Length of the Run so that the performance metric can be compared to other tasks within the same category, i.e. reverse trajectory to reverse trajectory.

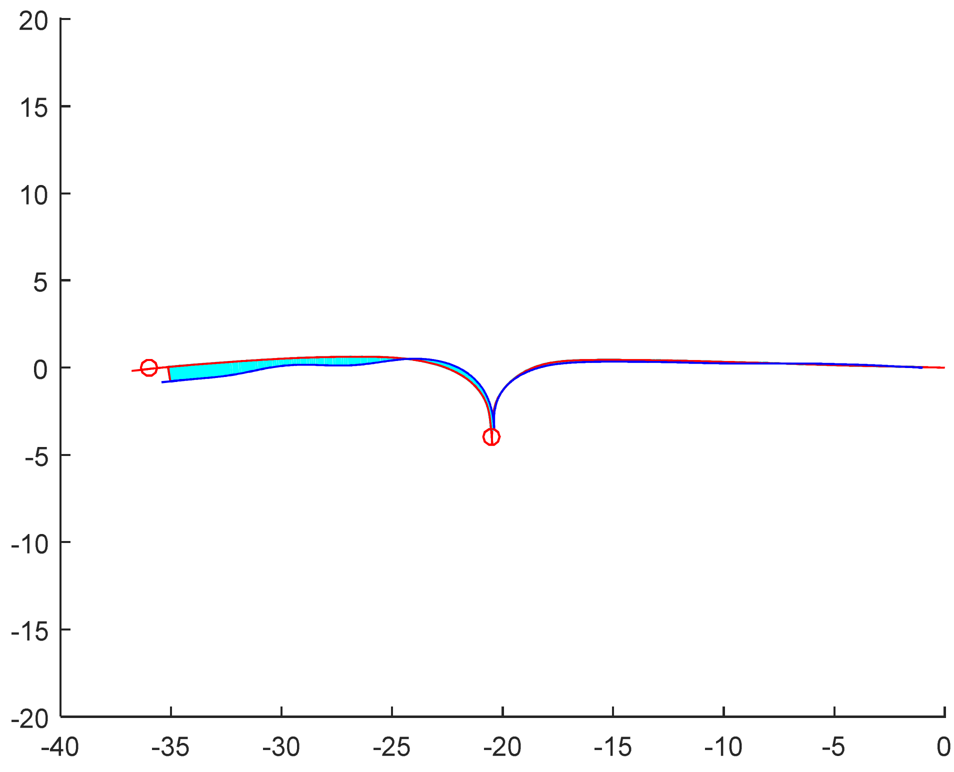

Figure 5-1 Visualization of Trajectory Performance Metrics. Path taken by remote operator (blue). Optimal Path (red). Area between paths (light blue). Check points (red circles).

5.1.1.2 Control Signals Performance Metrics

The second category, control signals performance, identifies the subject's response to the remote environment by assessing what control variables are being sent and how the vehicle responds to them. The Control Signals Performance metrics are:

- Corrections metrics calculate how many corrections are made by the operator during the execution of the task. This metric tries to describe how difficult a task is to the operator when compared to ground truth information. The metric is calculated by considering a correction to be when the parameter in hand is moved, i.e. when derivative of the value goes from zero to an amount and back to zero. Correction metrics are obtained from the operator station for:
    1. Steering signals [-].
    2. Acceleration signals [-].
    3. Brake signals [-].
- Velocity metrics provide information pertaining to how fluid the vehicle moved during the task. The following metrics are calculated from the distance parameter collected during the task execution. A difference is made between "Mean Speed" and "Moving Mean Speed". The mean speed is calculated by the general formula total distance over time. While the "Moving Mean Speed" is the average of the speed while the vehicle is in motion. The Velocity metrics obtained are:
    1. Maximum Speed [m/s].
    2. Mean Speed [m/s].
    3. Moving Mean Speed [m/s].
    4. Moving Standard Deviation Speed [m/s].
- Time performance metrics reveal how much time the operator required to perform the given task. The time is categories in to three categories, these being: moving

time, stopped time and initialization time. Initialization is the time required by the operator to start the system so as to be able to drive the vehicle. The moving and stopped time quantify how much the driver spent moving or stopped, respectively. The initialization time is calculated by counting the time since the system is setup on the remote side until the operator starts moving. The stopped time is calculated by count all the time that the vehicle had a speed of 0 [m/s] and the moving time is counted by all the time the vehicle hat a velocity larger the 0[m/s]. The Time Performance metrics are:

1. Total Time Moving [s].
2. Total Time Stopped [s].
3. Number of Stops [-].
4. Initialization Time [s].
5. Total Time [s].
6. Stop/Moving Ratio [-].
7. Stop/Total Ration [-].
8. Moving/Total Ratio [-].

5.1.1.3 System Variables Performance Metrics

The third category, system variables performance, goes through every control signal capturing their sent and received times and, through the means of synchronized clocks, calculates the time difference so as to have a latency value of each signal. The computed metrics are:

- The Latency performance metrics detail the time delay between when the signal was captured in the operator station and when said signal arrived on the remote vehicle. They do not account for roundtrip latency as explained in CHAPTER 4.

For each task, a latency profiles is calculated by mapping each time delay to a corresponding sent time. These metrics help understand how the system is being influenced by the 4G LTE network and guides troubleshooting in Section 5.3 . the calculated metrics are:

1. Latency Profile [-].
2. Control Signals Mean latency [ms], details the average latency that each task had, allowing for a point of comparison between tasks.
3. Control Signals Latency Standard Deviation [ms], similar to the average latency, this metric provides an idea of how spread-out each signal time delay is during each task.

Every one of these metrics is calculated for each of the tasks completed by each operator so as to have a clear idea of how they are performing when using the teleoperation system. However, as one can imagine, some metrics provide more information than others when predicting performance in each tasks. What's more, a metric that provides a clear description in a particular task may supply less information when used in another task. As an example, "stops" or "time stopped" when used in the straight trajectory tasks provide little to no information, but when compared in path following tasks it illustrates how difficult the task may be. For this reason, though this study calculates all of the above metrics, only select metrics are detailed with the intent of highlighting performance features. The selected metrics are chosen because: 1- they help illustrate difficulties within a particular task, 2- they help show contrast between tasks, and 3- they highlight system limitations. For a detailed breakdown of the values of all the performance metrics please refer to APPENDIX C. The metrics that will be highlighted for each task are:

- Maximum Distance Deviation

- Total time of execution
- Area Deviation
- Area Dev. In function of Time
- Maximum Speed
- Moving Mean Speed
- Number of Stops (not used in the straight trajectory task)
- Total time Stopped (not used in the straight trajectory task)
- Latency Mean
- Latency Standard Deviation

5.1.2 Results and Statistical Analysis

The three teleoperation tasks; 1- straight trajectory, 2- reverse trajectory and 3-path following, will be subject to the statistical analysis on each of the highlighted performance metrics. Each metric is first tested with a Kolmogorov-Smirnov test to determine the normality of the error metric. The metric variance is later tested with the F-test or a Levene test in order to determine whether the variances match the ground truths. Lastly, the T-test or Kruskal-Wallis test is used to determine whether the performance metrics share a common mean with the ground truth within a specific interval. If they do share a common mean, then the system can be said to be comparable to in-situ driving. Otherwise, if the last test rejects its null hypothesis, the system does not operate similar to local driving behavior. Statistical tests values for all metrics are detailed in APPENDIX D.

In order to further help visualize the results, the distribution of the metrics are shown in box-plots alongside the ground truth values for the corresponding performance metric. Recapping, ground truths are tasks completed with the driver situated in the vehicle, thus providing a point of comparison for remote operators.

Box-Plots provide a unique form of representing data in a simple graph that condenses relevant information. This allows the reader to extract key elements from data without relying heavily on numeral information and simultaneously visually recognizing important features within the data. Another useful feature is that boxplots help summarize information from different type of distribution, be it normal distributions or any other, due to how information is condensed and presented. Figure 5-2 shows how a box-plot is organized and what key point's represent. The center red line is the median; the upper and lower blue lines of the box are quartile 3 (Q3) and quartile 1 (Q1) respectively; the inter quartile range (IQR) is the space limited between Q3 and Q1 (IQR=Q3-Q1); the upper and lower whiskers are the highest and lowest data points within 1.5xIQR from Q3 and Q1; and the outliers are all points out of the ranges limited by the whiskers.

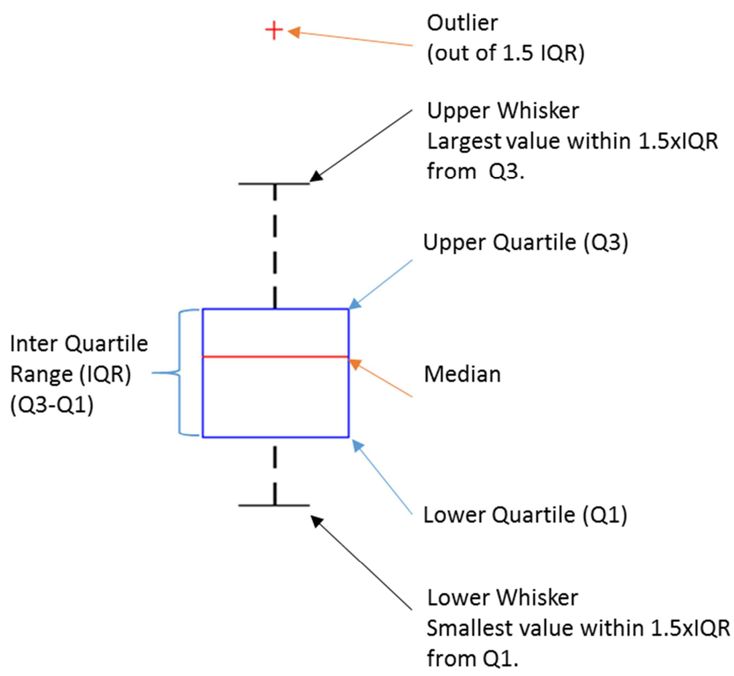

Figure 5-2 Description of Box-Plot Identifiers

As a mode of example actual data points are overlaid in a box-plot that summarizes the information in Figure 5-3.

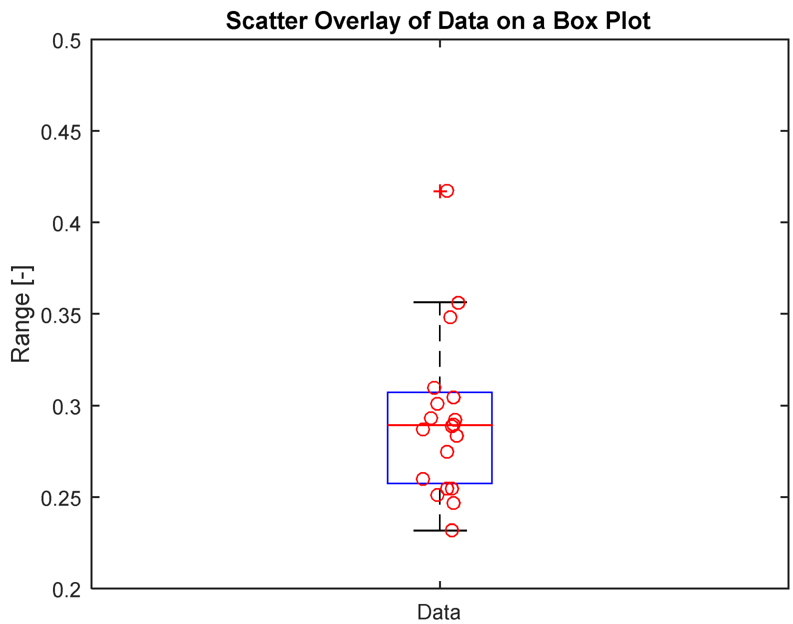

Figure 5-3 Actual Data Points overlaid on a Box-Plot

5.1.2.1 Straight trajectory task

To determine whether the system allows operators to complete tasks in a manner that may be considered “as well” as in-situ drivers, the performance metrics previously listed are subjected to the statistical tests. If the performance metrics are able pass the final T-Test or Kruskal-Wallis Test, then remote operation is considered to be feasible and the teleoperator performed comparable to a local driver.

In this case, the first performance metrics studied are the most typical metrics encountered in similar studies, these being the maximum deviation from path and the total time of the run, shown in Figure 5-4 and Figure 5-5. Here, both metrics reject the Kolmogorov-Smirnov test, implying that they do not follow a normal distribution at a significance level of α of 5%. Furthermore, the Levene Test is rejected at the same significance level, therefore their variances are not comparable to the ground truths. With this information, the Kruskal-Wallis test is applied and subsequently rejected with a significance level of α equal to 5% and with p-values of 1.01e-03 and 3.04e-04 respectively.

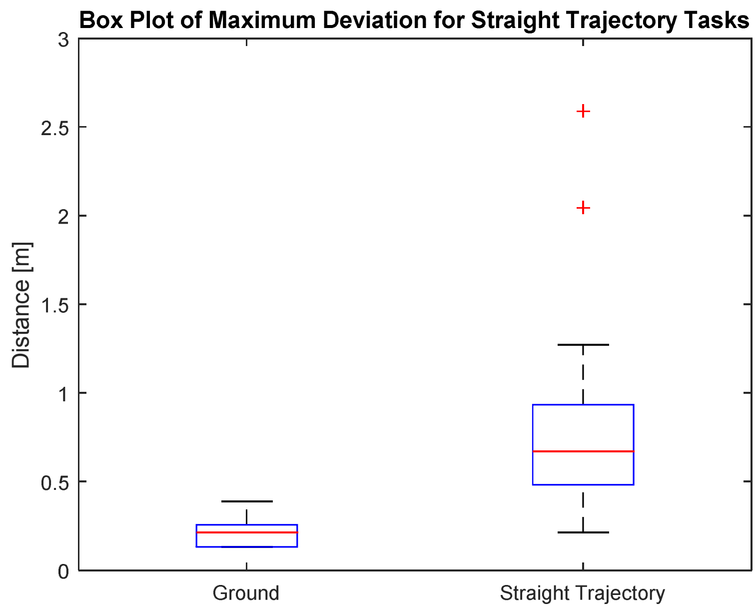

Figure 5-4 Box Plot of Maximum Deviation for Straight Trajectory Tasks

Though the maximum deviation from the path is on average 0.91 [m], the ground runs averaged .22 [m], far less than remote operation. On top of this when viewing the total time of the run, one observes large variances within the metric, which is then compounded to the fact that the remote operation median is roughly twice that of the ground truth.

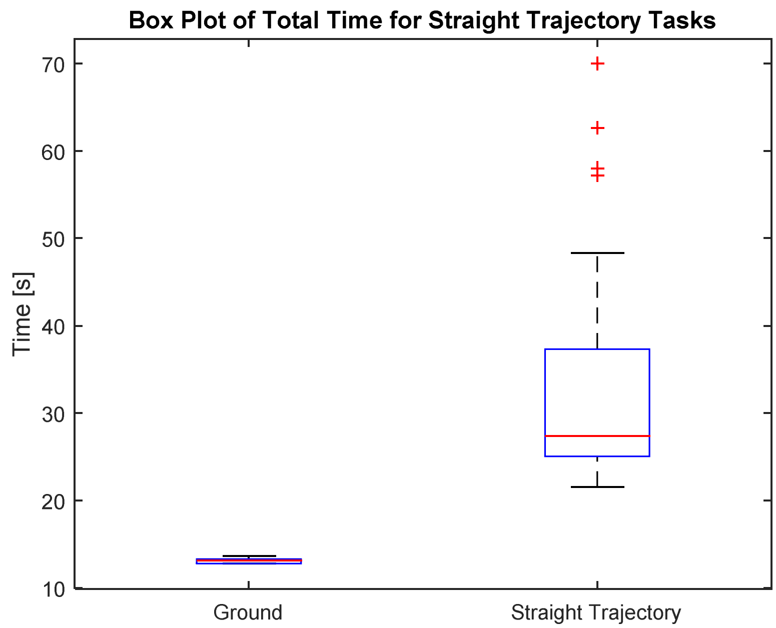

Figure 5-5 Box Plot of Total Time for Straight Trajectory Tasks

Continuing the statistical analysis, the Area Deviation and Area Deviation in Function of Time, shown in Figure 5-6 and Figure 5-7, are subjected to the previous tests. Again, both metrics fail the KS-test and the Levene test at an α of 5%. They also reject the Kruskal-Wallis null hypothesis with p-values of 1.68e-04 and 3.50e-04 respectively.

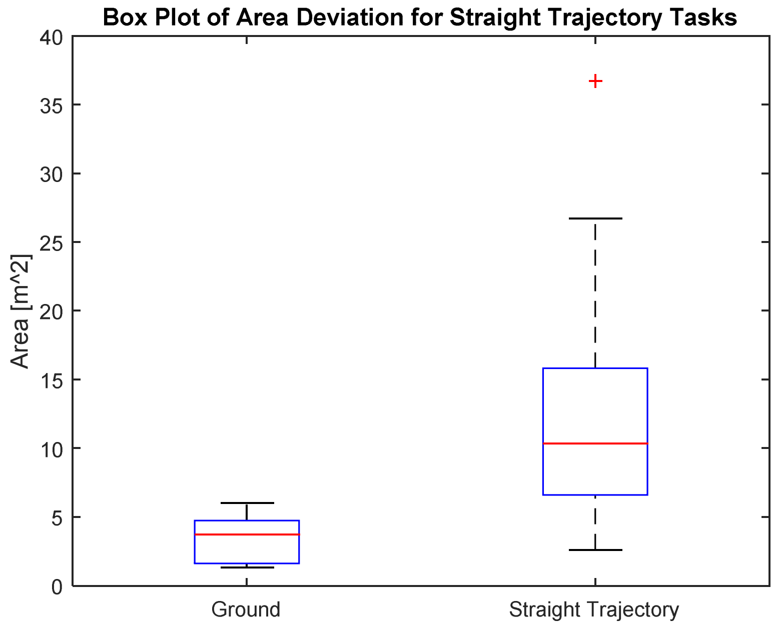

Figure 5-6 Box Plot or Area Deviation for Straight Trajectory Tasks

Once again, the teleoperation system did not allow equal performance when compared to ground truths for both metrics, further establishing that some type of limitation exists. However, it should be noted that even though the great majority of the operators did not achieve expected results, some participants were able to perform as well as in-situ drivers, falling within both the 1st and 3rd interquartile bounds of the ground truth runs.

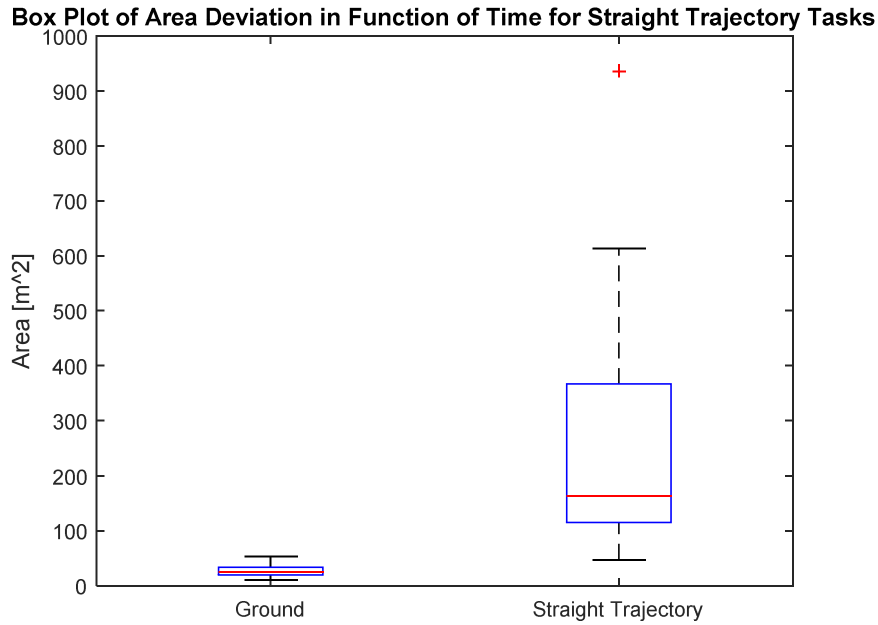

Figure 5-7 Box Plot of Area Deviation in Function of Time for Straight Trajectory Tasks

Remembering that one of the objectives in this task was for the operator to achieve the highest speed possible and maintain it throughout the run, the Maximum Speed and Mean Speed metrics are analyzed. Contrary to previous examples, both metrics fail to reject the KS-test and F-test at an α of 5% implying that they resemble a normal distribution and both have similar variances to those of the ground runs. The corresponding boxplots are shown in Figure 5-8 and Figure 5-9. However, both two-sample T-test reject the null hypothesis, which indicates that neither mean is comparable to those of the ground truths.

Lastly, the average and standard deviation of latency are shown in Figure 5-10. It's important to highlight that the mean is well within the acceptable limits when compared to other studies. Even though the latencies are within expected ranges, they do not follow a normal distribution as would be expected, due to the fact that the average latency KS-test rejects the null hypothesis at a p-value of 0.0139.

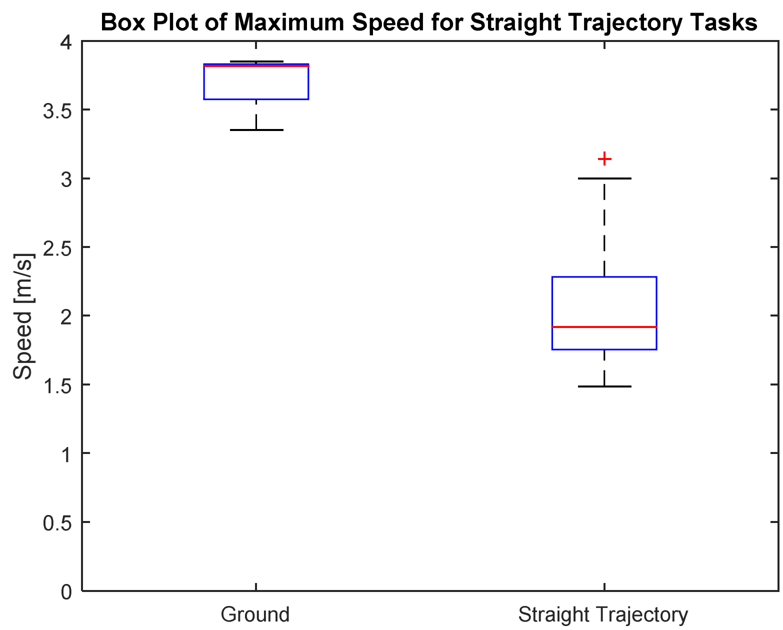

Figure 5-8 Box Plot of Maximum Speed for Straight Trajectory Tasks

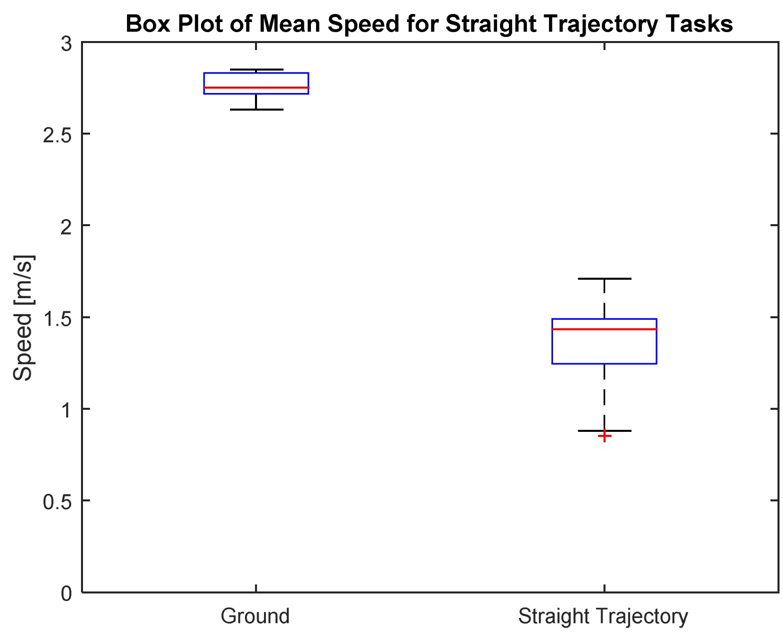

Figure 5-9 Box Plot of Mean Speed for Straight Trajectory Tasks

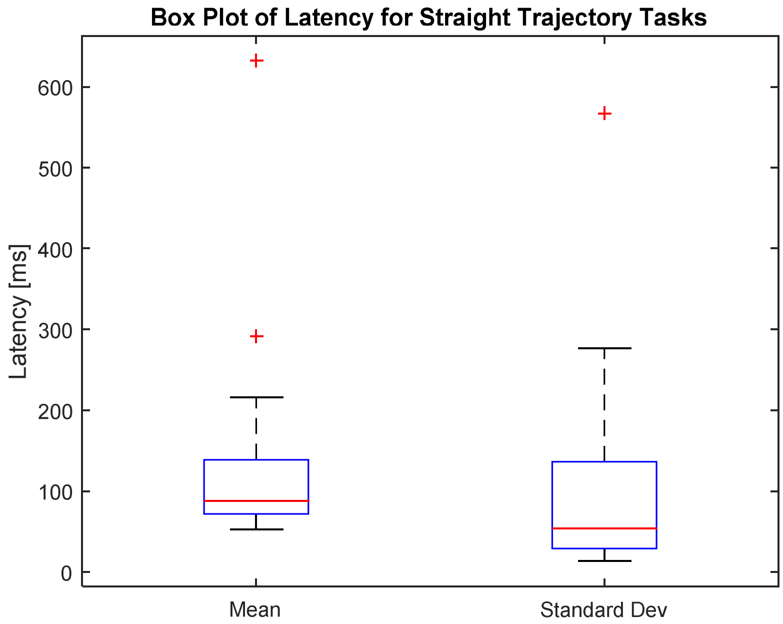

Figure 5-10 Box Plot of Latency for Straight Trajectory Tasks

Summarizing the straight trajectory task results, one can see that the majority of the T-tests or Kruskal-Wallis tests reject the null hypothesis that the means belong to the same distribution. This indicates that none of the performance metrics were able to establish that their means are statically similar to those of the ground truths. Therefore, based on just these results, it would seem that the system does not allow for performance similar to that of in-situ drive. However, some operators were able to achieve performance metrics that fell within the interquartile range Q1 and Q3 of the ground truths. This suggests that, even though most drivers could not perform as expected, perhaps a more experienced driver could perform on par to in-situ drivers.

5.1.2.2 Reverse Trajectory task

The next task that will be subjected to statistical analysis is the reverse trajectory task. Again, attention is directed to metrics that detail the Maximum Deviation from the Path and the Total Time it took the participants to complete the given task. In this case, both metrics fail to reject the Kolmogorov-Smirnov test with a significance level of α equal to 5%, establishing that the metrics follow a normal distribution. However, they both reject the F-test at the same α. Furthermore, they also reject the two-ample T-test with p-values of 1.204e-07 and 7.542e-11 respectively.

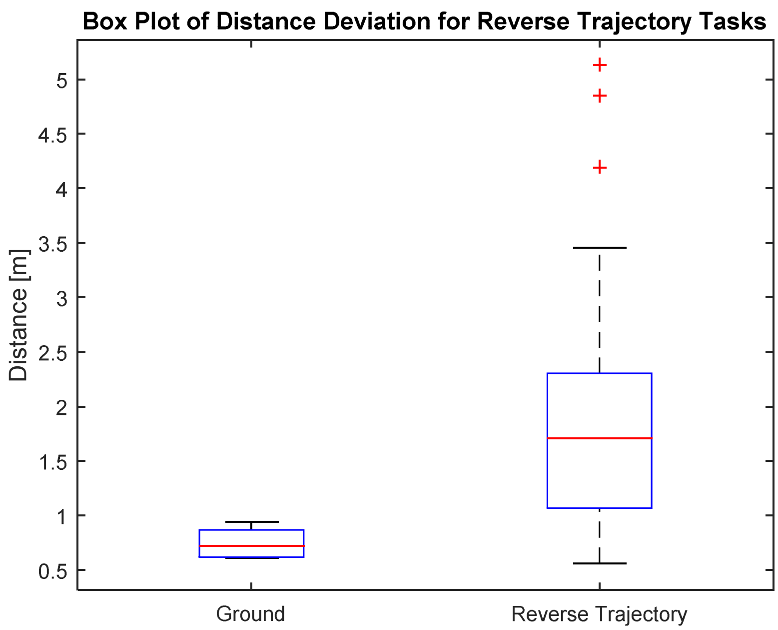

Figure 5-11 Box Plot of Distance Deviation for Reverse Trajectory Tasks

Visually inspecting the box-plots in Figure 5-11 and Figure 5-12, one can see that a great amount of variance exists in both metrics. On top of this, both show a large presence of outliers, hinting that the task at hand may represent a higher degree of difficulty when compared to straight trajectory tasks. Nevertheless, some operators were still able to outperform in-situ drivers, suggesting once more that optimal performance is possible.

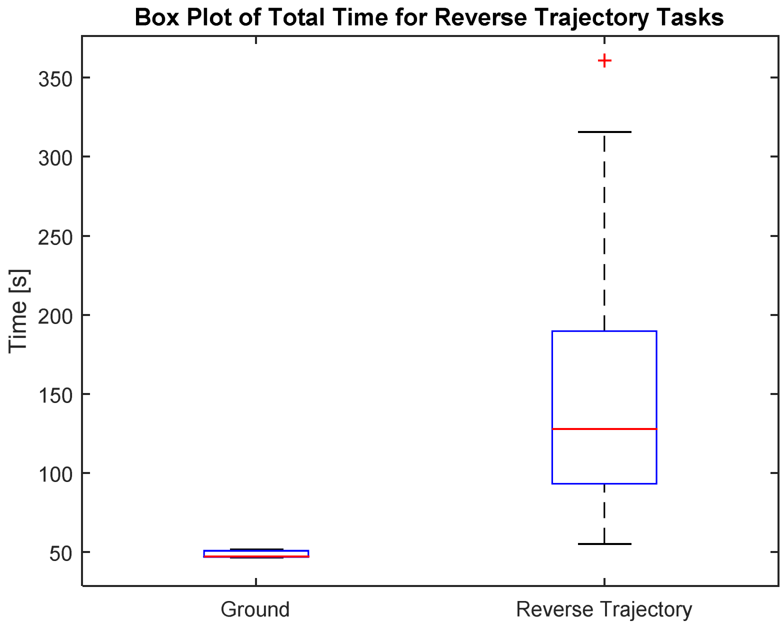

Figure 5-12 Box Plot of Total Time for Reverse Trajectory Tasks

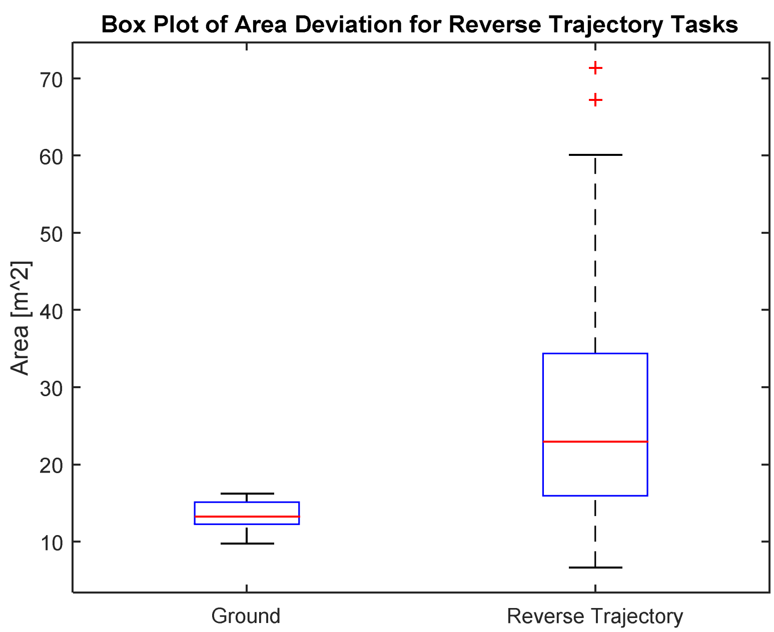

Figure 5-13 Box Plot of Area Deviation for Reverse Trajectory Tasks

Continuing the analysis, the metrics Area Deviation and the Area Deviation in Function of Time are inspected and illustrate in Figure 5-13 and Figure 5-14. The KS-test reveals that the former fails to reject the null hypothesis while the latter rejects it, both with at a significance level set to α at 5%. But once more the F-test and Levene tests are rejected. Using this information in the two-sample T-test and Kruskal-Wallis test, it again rejects the hypothesis with p-values of 7.88e-06 and 7.83e-04. These results further cement the tendencies that have been seen until now.

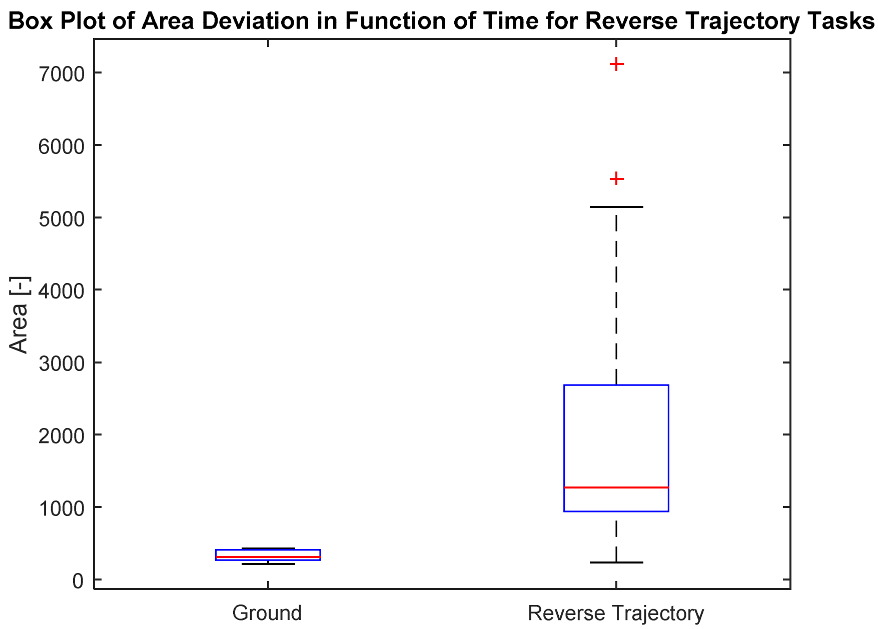

Figure 5-14 Box Plot of Area Deviation in Function of Time for Reverse Trajectory Tasks

When reviewing the Maximum Speed metric, shown in Figure 5-15, intuitively one can see that it might share the same mean as the ground truth. Applying the statistical analysis, the KS-test does not reject the null hypothesis while the F-test does. However, in this particular case the two-sample T-test does not reject the null hypothesis with a p-value of 0.9214, implying that it shares a common mean. Unfortunately, when the Moving Mean Speed, shown in Figure 5-16, is submitted to the same statistical test it rejects the Kruskal-Wallis test, showing once again that performance cannot be said to be comparable to local operation.

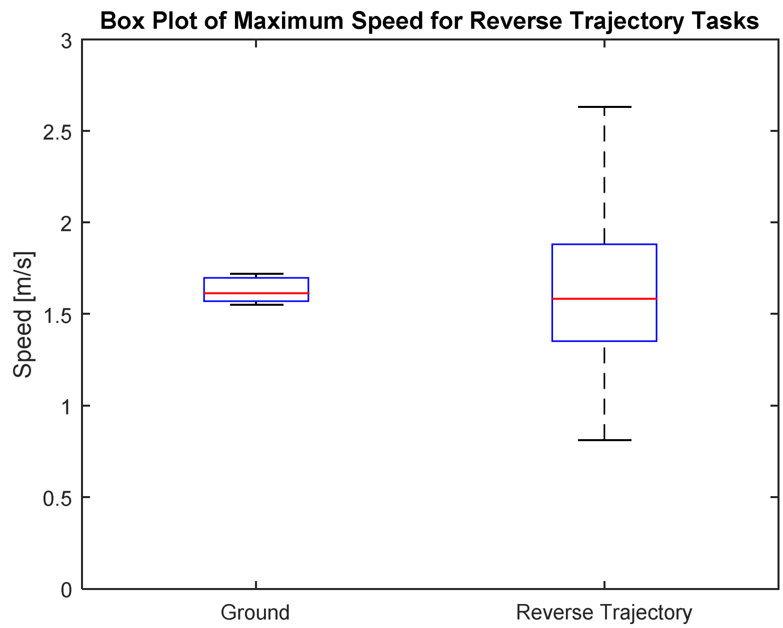

Figure 5-15 Box Plot of Maximum Speed for Reverse Trajectory Tasks

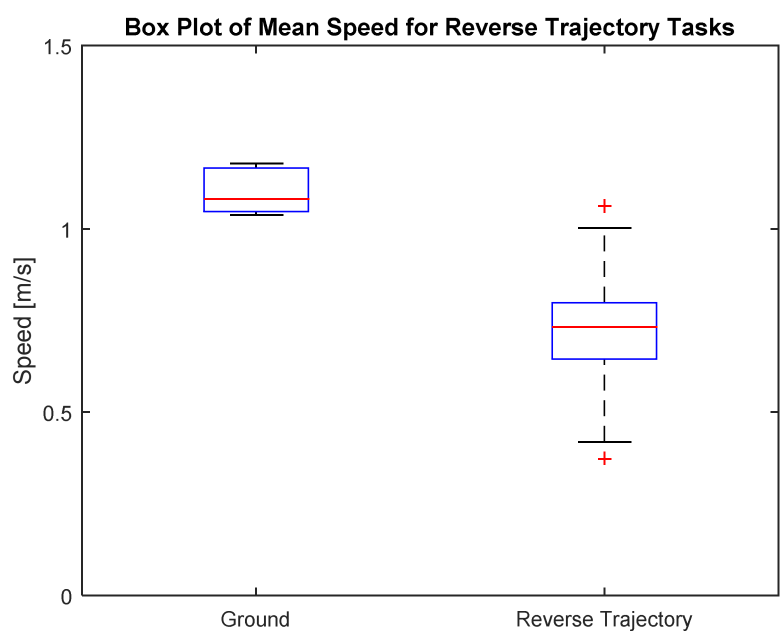

Figure 5-16 Box Plot of Mean Speed for Reverse Trajectory Tasks

The results seen in the previous metric show unexpected behavior concerning speed. More specifically, it would seem that the operators are trying to accelerate more than necessary, but fail to maintain a high average speed. Due to this, the Total Stops and Total Time Stopped metrics are scrutinized in an attempt to see if relevant information can be extracted from these. The box-plots for these metrics are illustrated in Figure 5-17 and Figure 5-18.

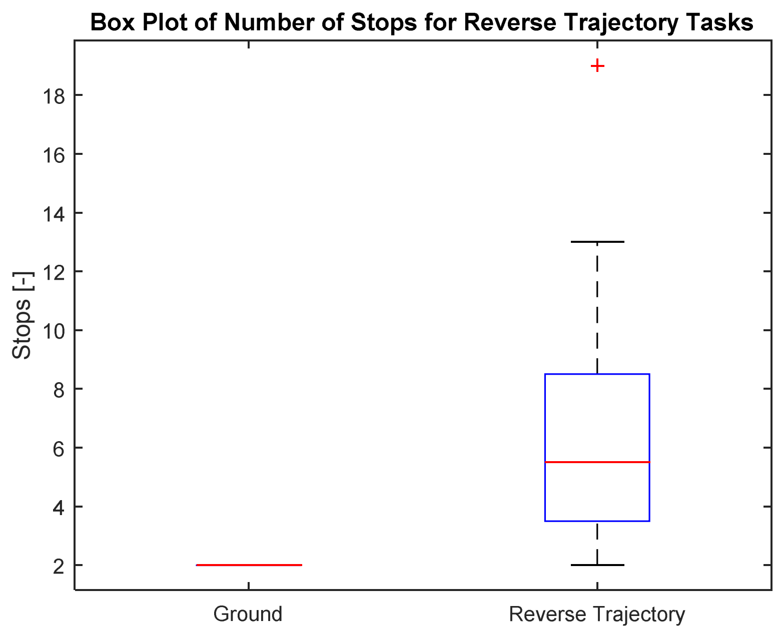

Figure 5-17 Box Plot of Number of Stops for Reverse Trajectory Tasks

Here a new tendency, not seen in the prior task, arises. By visual inspection, the metrics show a significant increase in the degree of complexity. More precisely, this task requires only 2 stops, one when the vehicle is first parked and a second when it stops at the final check point. This is explicit when studying the ground truth metric that shows only two stops are needed to complete the test. However, the teleoperator performance metric shows that the drivers stop more times than expected. This tendency is further amplified when studying the Total Time Stopped metric, which also shows that a substantial amount of time is spent with the vehicle stopped. Furthermore, and not surprisingly, both two-sample T-tests and Kruskal-Wallis test reject the null hypothesis of a common mean with p-values of 6.22e-09 and 3.04e-04 respectively.

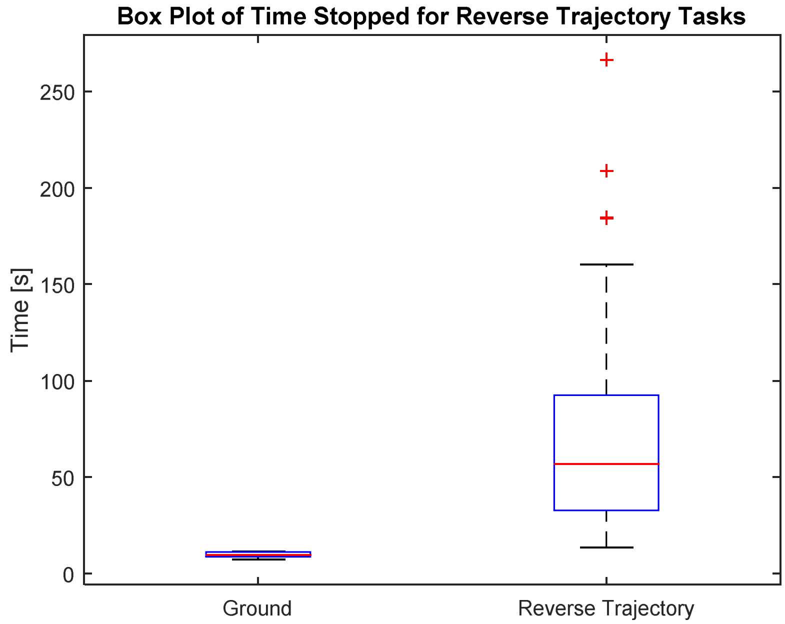

Figure 5-18 Box Plot of Time Stopped for Reverse Trajectory Tasks

Taking it a step further and trying to determine whether there are any patterns regarding where operators stopped their vehicles, the unexpected stops are plotted over the ideal path in Figure 5-19. At first glance, one notices that a great majority of the interruptions are concentrated at the end of the first segment, while the drivers are backing up to the parking area, and at the beginning of second segment while the vehicles are pulling out of the parking area. Several reasons may exist as to why there is an apparent concentration of detentions in these areas, but the predominant reason that is further explored in Section 5.3 pertains to possible latency issues.

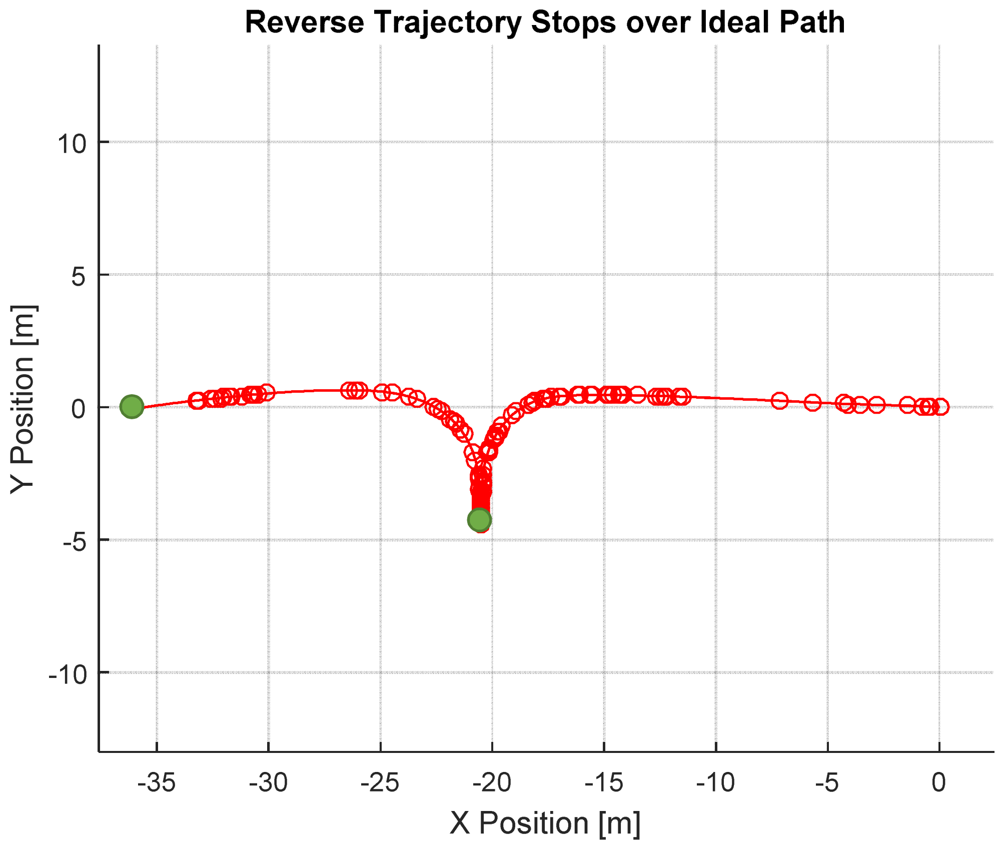

Figure 5-19 Reverse Trajectory Stops Plotted over the Ideal Path. In Green are the ideal locations for stopping that in-situ drivers achieved consistently.

To end with the reverse trajectory statistical analysis, the average and standard deviation of the latency are shown in Figure 5-20. In this occasion, though the mean latency is within acceptable ranges, the overall spread of the average and variance are evidently larger than in the previous task, and in some instances surpass 1000 [ms]. This abnormally high standard deviation hints at the fact that, though some tasks are completed with relatively stable time delays, others present highly variables time delays which is believed to significantly hinder operator performance .Additionally, the average latency rejects the KS-test with a p-value of 0.0149, implying that it does not follow a normal distribution, contrary to what would be expected.

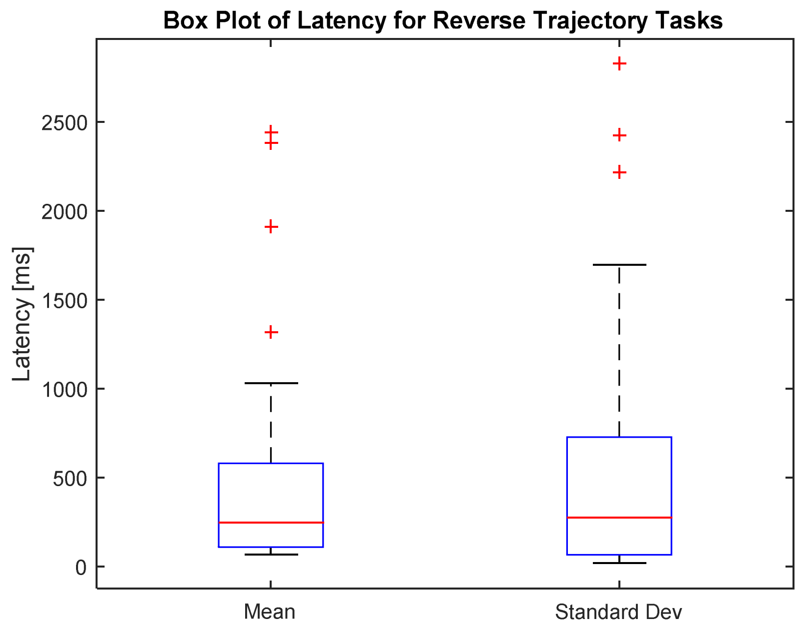

Figure 5-20 Box Plot of Latency for Reverse Trajectory Tasks

Summarizing the reverse trajectory task results, the statistical analysis shows that almost all of the performance metrics do not share a common mean with those of the ground truths. What's more, when a metric does not share the same average, the metrics greatly underperforms the corresponding ground truth.

Up to this point the results do not seem promising, additionally the metrics are starting to show signs that they systematically fail to achieve expected outcomes. This is further cemented by the unexpected concentration of vehicles stops in certain locations. These issues shall be further analyzed in Section 5.3 when trying to determine the underlying causes for systems limitations.

5.1.2.3 Path Following Task

Following similar logic as in the previous cases, box plots of the highlighted metrics are shown in Figure 5-21 and Figure 5-22, along with the statistical analysis that attempts to determine whether the system allows acceptable performance.

Contrary to the prior tasks, the Maximum Deviation and the Total Time indictors both fail to reject the Kolmogorov-Smirnov null hypothesis, i.e. their distribution is normal at a significance of α equal 5%, and their variance do not follow that of the ground truth at the same α, as shown by the F-test.

With this, the means of the max deviation and total time are compared and again the two-sample T-test rejects the null hypothesis with a p-value of 1.01e-3 and 9.40e-12 respectively. Both metrics show a large deviance from the expected results, diverging by more than 4 [m] from the ideal path and taking more than twice the required time to complete the path following task.

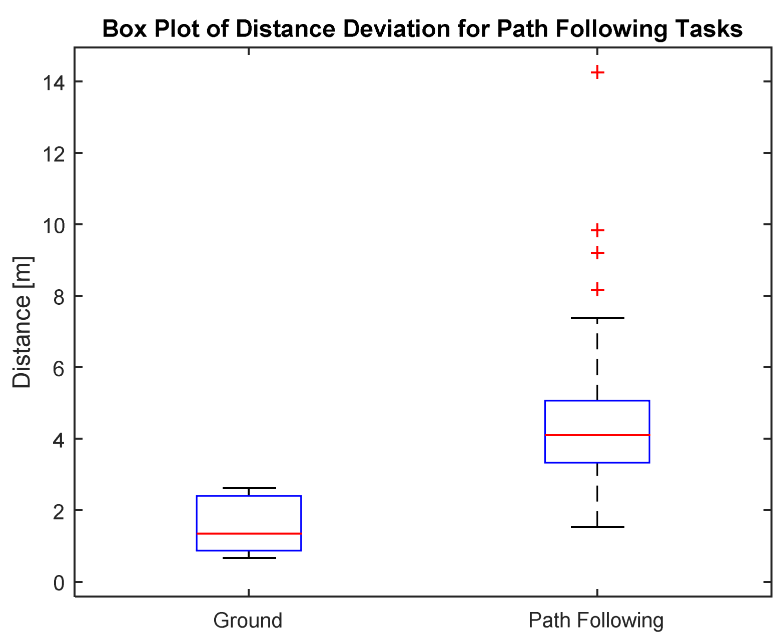

Figure 5-21 Box Plot if Distance Deviation for Path Following Tasks

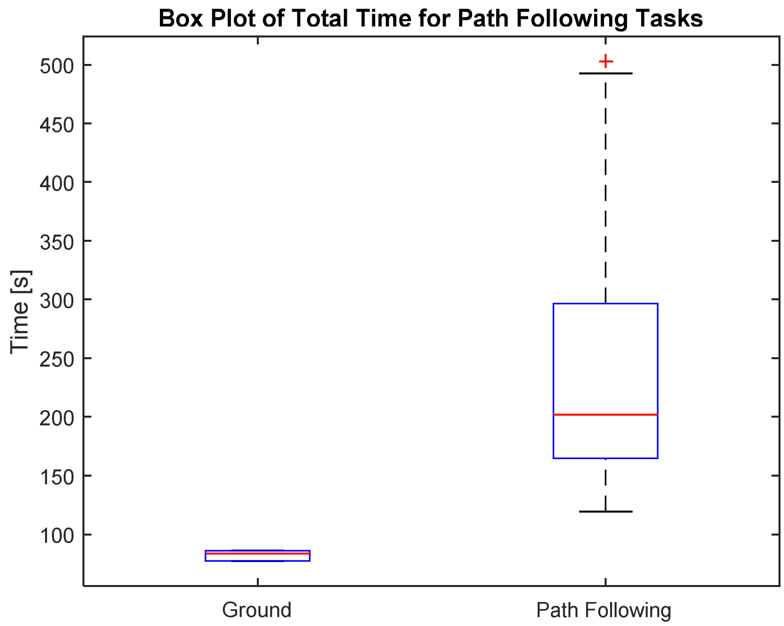

Figure 5-22 Box Plot of Total Time for Path Following Tasks

Not content with only comparing these two metrics, focus is placed on the other calculated metrics in order to widen the analysis and substantiate the final results. Taking into account the Area Deviation and Area Deviation in function of Time metrics, these also fail to reject the KS- test null hypothesis at α 5% significance, but reject the F-test hypothesis of equal variance. Subsequently we compare the means with the two-sample T-test test and determine that they reject the null hypothesis with a p-value of 4.18e-10 and 5.01e-11 respectively. This further drives the idea that system operators are underperforming when compared to in-situ drivers by approximately 3 to 12 times depending on the performance metric, as seen in Figure 5-23 and Figure 5-24.

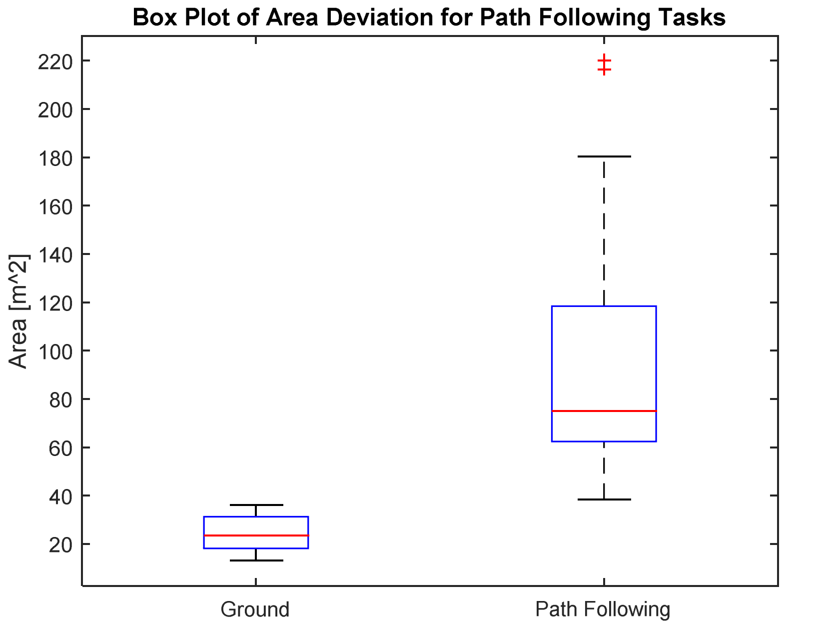

Figure 5-23 Box Plot of Area Deviation for Path Following Tasks

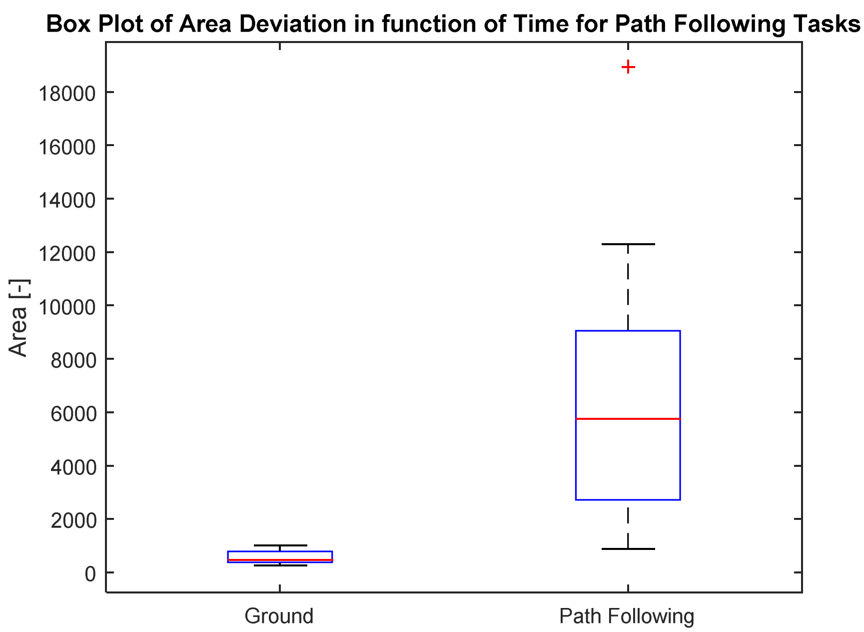

Figure 5-24 Box Plot of Area Deviation in Function of Time for Path Following Tasks

Comparing the Maximum Speed and Moving Mean Speed plotted in Figure 5-25 and Figure 5-26, a different outcome to that witnessed in the reverse trajectory task is observed. That is, the speeds are not as close to the anticipated ground values and the two-sample T-test test rejects the null hypothesis (they do not share the same mean) at a p-value of 2.96e-12 and 4.65e-18 respectively.

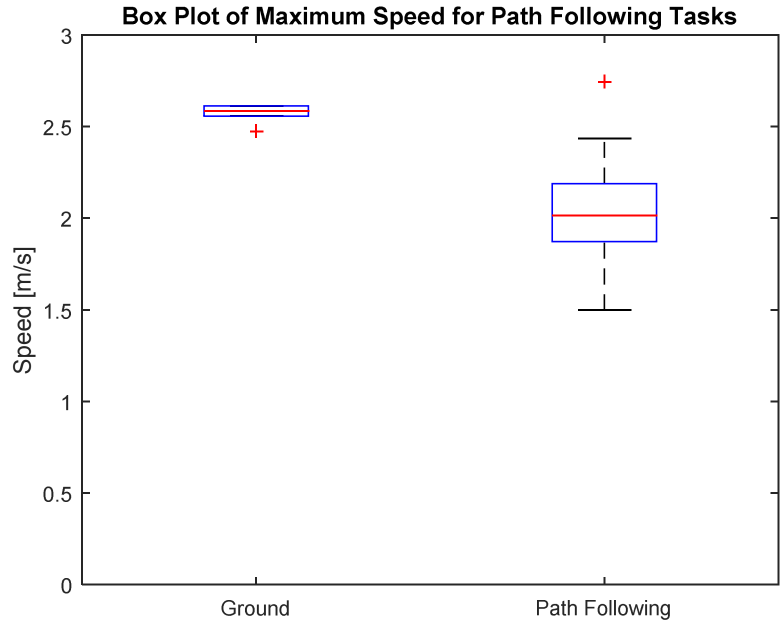

Figure 5-25 Box Plot of Maximum Speed for Path Following Tasks

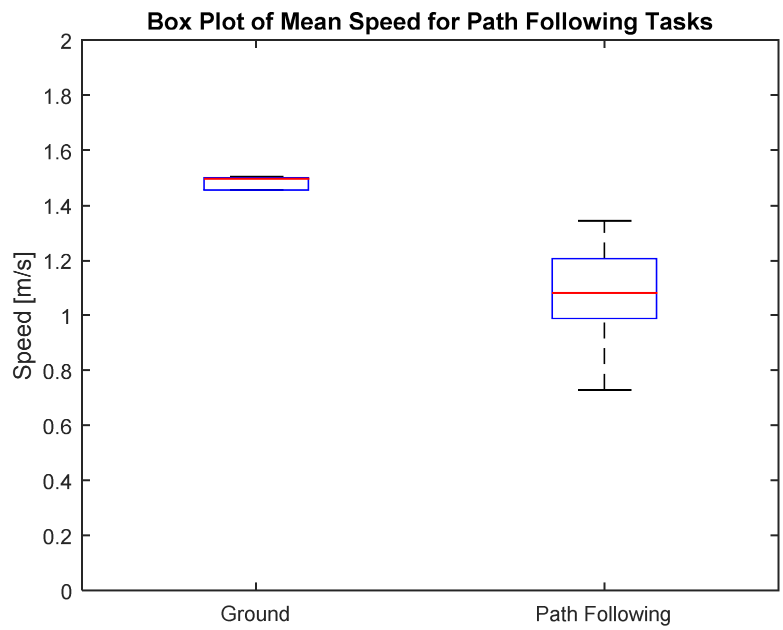

Figure 5-26 Box Plot of Mean Speed for Path Following Tasks

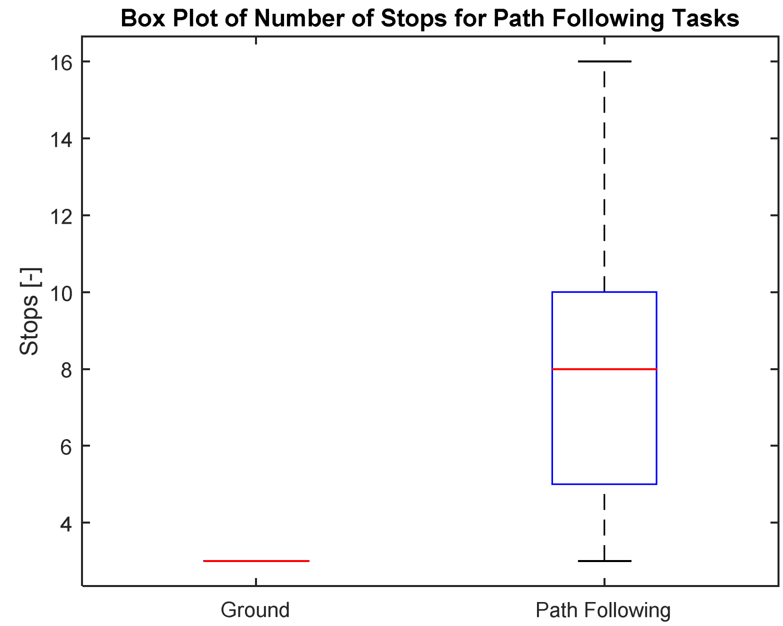

Figure 5-27 Box Plot of Number of Stops for Path Following Tasks

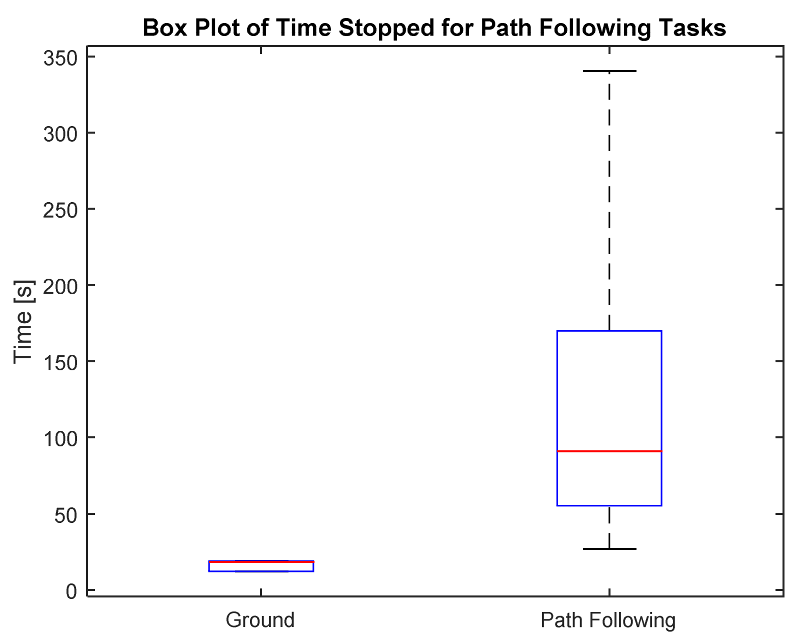

Figure 5-28 Box Plot of Time Stopped for Path Following Tasks

Nevertheless, checking the same stop metrics as in the reverse trajectory task, the Number of Stops in the run and Time Stopped are examined in Figure 5-27 and Figure 5-28, and the same hesitant behavior is observed as in the reverse trajectory task. Here, the null hypotheses rejections and non-rejections are the same as in the previous task with even lower p-values and the vehicle stops are plotted over the ideal path to see if there are any patterns, illustrated in Figure 5-29. Though the pattern doesn't exactly follow that of the reverse trajectory, a concentration of stops is seen entering and during curves in the path following task.

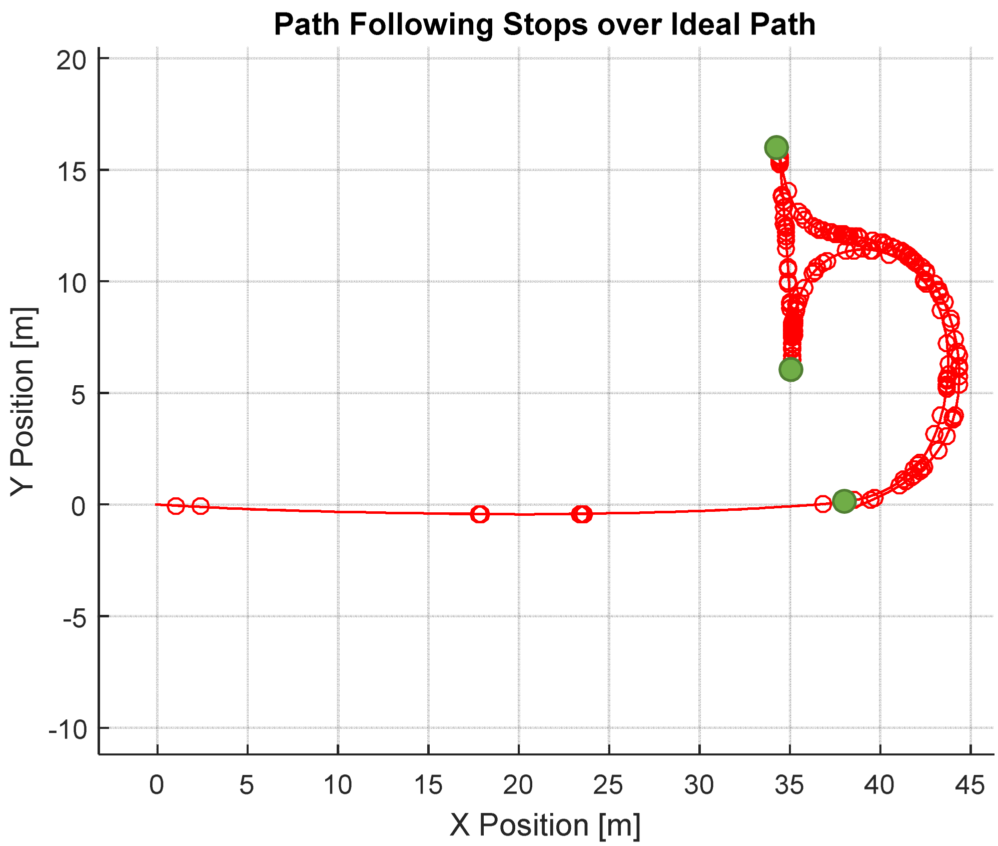

Figure 5-29 Path following Stops Plotted over the Ideal Path. The green dots shoe optimal stop points.

Lastly, the average latency and standard deviation are displayed in Figure 5-30, so as to have somewhat of a quantitative understanding of these parameters in the given task. Here the average latency fails the KS-test null hypothesis at a p-value of 0.0171. The significance of this, similar to the previous task, is that though we would anticipate that the average of the latency to follow a normal distribution it unfortunately is does not adhering to what's expected, highlighting an underling presence of error that we will further be analyzed in Section 5.3 5.3 .

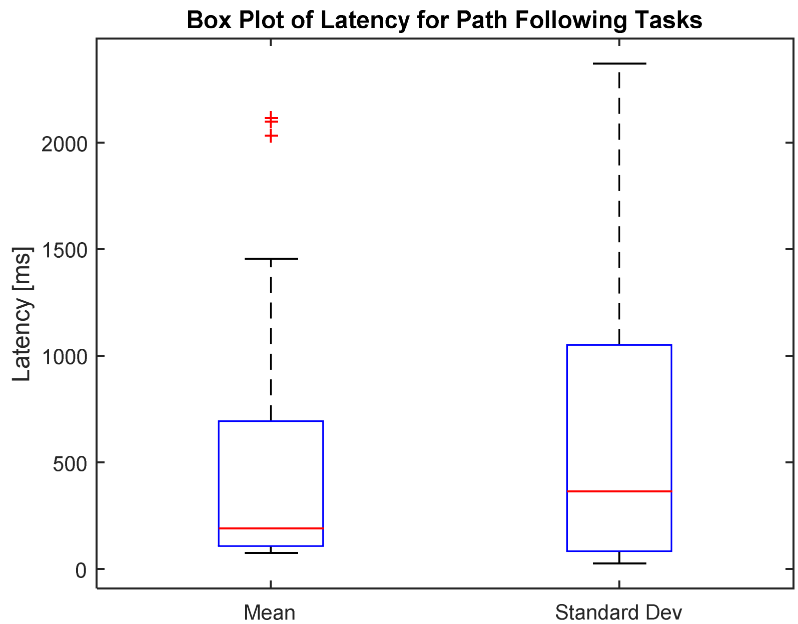

Figure 5-30 Box Plot of Latency for Path Following Tasks

5.1.3 Results Summary

Reviewing the results of the completed statistical tests, it can be seen that the performance metric for each operator and task generally do not compare significantly to the ground truths previously measured. Moreover, when comparing the metrics to ideal values, these grossly underperform, implying that the remote operators are not capable of achieving in-situ performance through the teleoperation system.

More concretely, Straight trajectory tasks fail to provide significant statistical similarity to ground truths in 13 of the 20 metrics measured. Though this is not overwhelmingly skewed to the rejection of the hypothesis, when analyzing Reverse Trajectory Tasks and Path Following Tasks, the difference is much larger.

In Reverse Trajectory Tasks, the mean comparison statistical test is rejected 17 out of 20 times. Concurrently, the Path Following Task rejects statistical similarities between the means 18 out of 20 times.

With these results, this works confidently rejects the principle hypothesis that “A vehicle can be controlled over a 4G LTE network streaming HD video feedback” due to important system limitations.

5.1.4 Questionnaire

In this section, the results to the questionnaire that each participate completed are detailed. After completing every tasks, the subjects were asked fill a questionnaire that sought to obtain qualitative metrics regarding the teleoperation system. As seen in the questionnaire in APPENDIX B, the questions span across various features that help narrow down possible causes for reduced performance experienced during teleoperation by explicitly listing them and petitioning the driver to rate how said factor influence his performance. Each person is asked to rate the individual compare the degree of influence between certain factors.

After compiling and analyzing the results, this study has chosen to detail 4 main classifications that offer an improved grasp of what the participants believe. On top of this, the insight that these categories provide will help guide the analysis presented in the subsequent sections. The categories are:

- Camera Location Comparison
- Video Feedback
- System Latency Levels

- Overall Perceived Performance

5.1.4.1 Camera Location Comparison

When analyzing the participant's perception of the camera position, the relevant questions to review are:

- Q16: I preferred driving the vehicle with the cameras positioned…
- Q17: With the camera positioned outside, my spatial awareness was…(view seen in Figure 5-32)
- Q18: With the camera positioned inside, my spatial awareness was…(view seen in Figure 5-31)

Figure 5-31Camera Position- Inside Vehicle

The results to each of these questions are shown in Figure 5-33. From the image, one can see that participants overwhelmingly preferred the camera positioned on the inside of the cart, seen by the answers to Q16. And when asked how they believed that they performed with the camera on the inside of the cockpit, Q18, the majority believed they performed close to excellent. Though mixed signals are expressed when answering Q17, where the distribution is almost uniformly distributed form poor to excellent performance.

Figure 5-32 Camera Position – Outside Vehicle

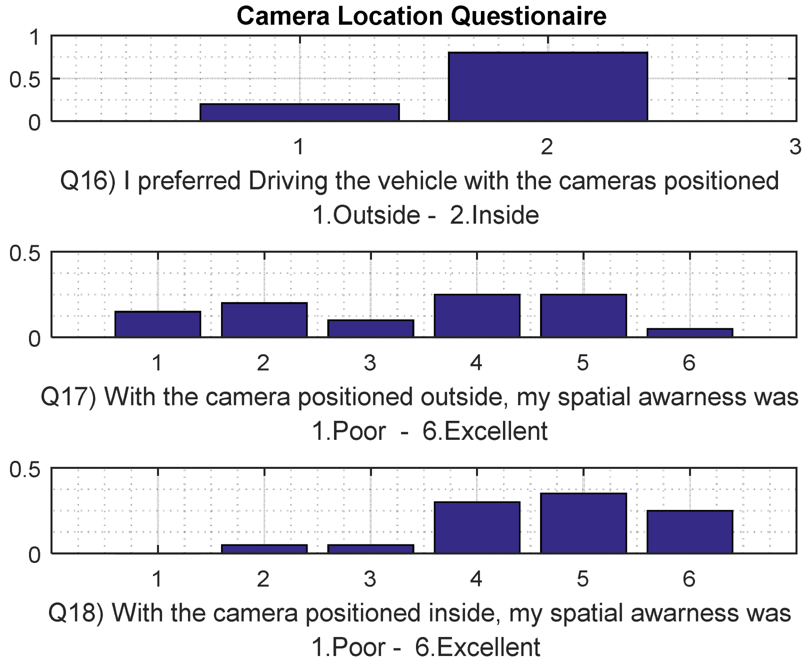

Figure 5-33 Bar Graph of Questions Relating to Camera Location

5.1.4.2 Video Feedback Questionnaire

When quantifying the significances that video feedback played on the individual's performance, the subjects had to answer:

- Q1: Did you experience video quality problems?
- Q2: Of the issues related to video quality, how good was the resolution?
- Q3: Of the issues related to video quality, how good was the frame rate?
- Q4: How did the video quality affect your performance?
- Q5: Which parameter, if improved, would most affect your performance?

From Figure 5-34, one can see that operators either experienced "a lot of problems" or "no problems" when driving the remote vehicle, from Q1, and small percentages experienced performance in between said extremes. Furthermore, from Q4, most participants believed that video quality heavily affected their performance. Additionally, when directed to choose between which parameter of video quality would most affect their performance if improved, the great majority chose to improve the frames per second of the video stream.

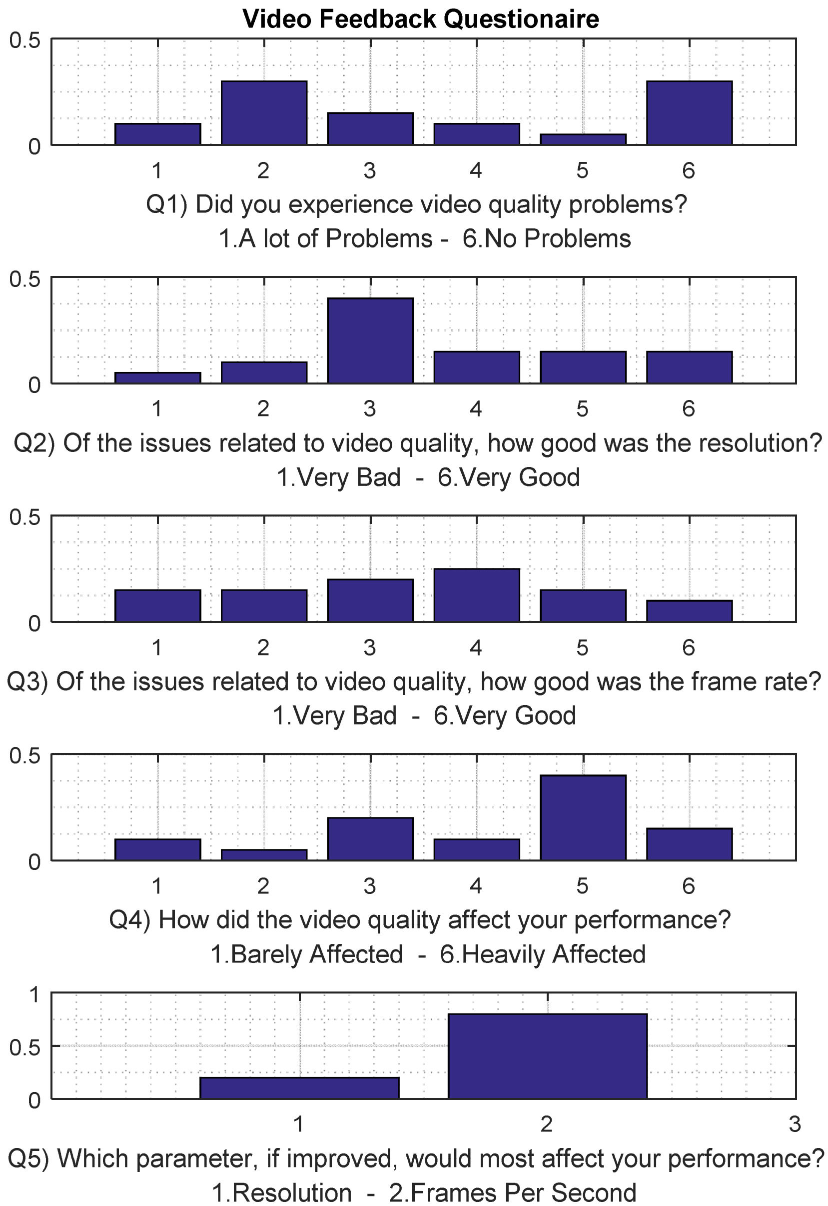

Figure 5-34 Bar Graph of Questions Related to Video Feedback

5.1.4.3 System Latency Questionnaire

When asked to answer questions regarding the systems time delay perceived by the participants, they were asked:

- Q25: How much time delay in controls did you experience?
- Q26: Rate the variation of the time delay.
- Q27: The time delay I was exposed to affected my performance… (Significantly-Very Little)

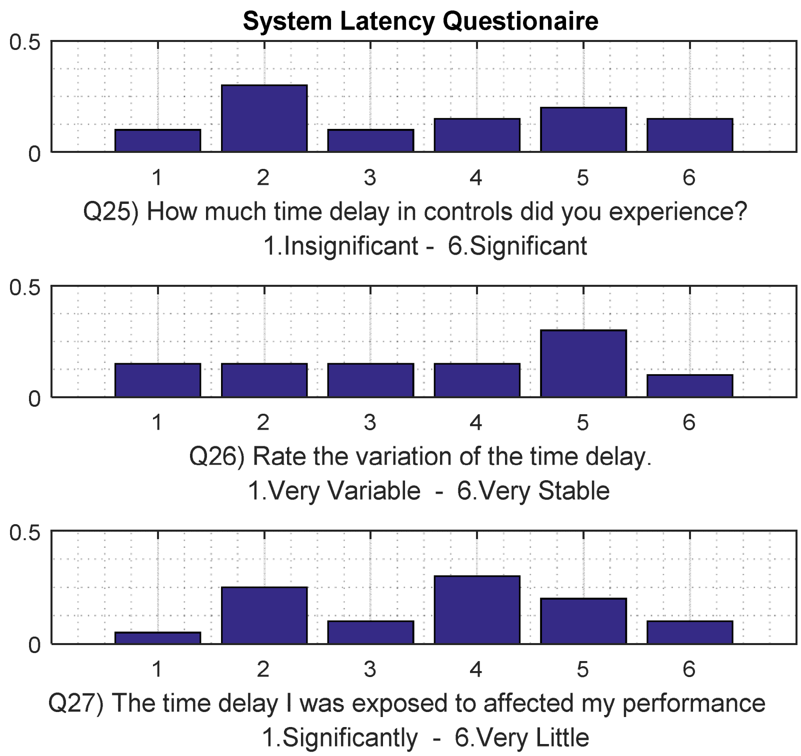

Figure 5-35 Bar Graph of Questions Regarding System Latency

From Figure 5-35, a clear tendency regarding user opinion to system latency is not observable. In question Q25, approximately 30% of the users believe that they did not experience significant time delay in control signals, but 50% believe that they did experience some degree of latency. Furthermore, when asked if time delay affected their performance, the results again bring back mixed feelings, not being able to concretely determine whether latency did or did not affect individual performance.

5.1.4.4 Overall Perceived Performance

Finally, when asked to evaluate the individual performance that each participant had, the relevant questions asked were:

- Q28: My performance was… (Inadequate-Adequate)
- Q34: What most hindered my performance was...(Answers shown in Table 5-1)

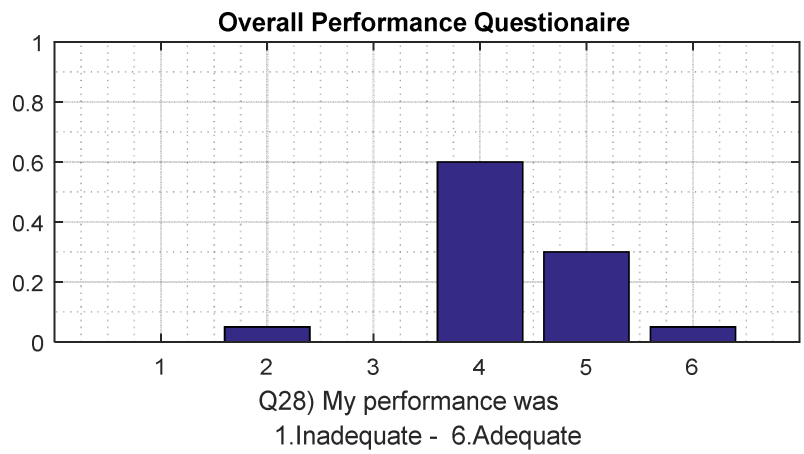

Figure 5-36 Bar Graph of Questions Relating to Overall Performance

From Figure 5-36, one can clearly see that the great majority of the participants believed that they completed the driving tasks at least adequately. An interesting fact, when compared to the statistical results analyzed in the previous section.

Additionally, even though question Q34 is open ended the participants answers were able to be categorized into 5 categories. These categories are order and shown in Table 5-1.

Table 5-1 Answers to Question 34) what most hindered my performance was…

Main Feature that Hinders Performance	Relative Frequency
Video Quality - Resolution	0.10
Video Quality – Frames Per Second	0.25
Time Delay of Control Signals	0.45
No Force Feedback	0.10
Camera Position – Field of View	0.10

Reviewing the collected data and the statistical results obtained, it is clear that the initial hypothesis is rejected. That is, the teleoperation system does not allow for "a vehicle to be controlled over a 4G LTE network streaming HD video Feedback" equivalent to a regular driver, as defined in this study. Though the hypothesis has been rejected, this study has still not determined whether the camera position significantly influences teleoperation, nor has it determined possible causes for the system underperformance.

The rest of this chapter focuses on taking a more in-depth look at the variables collected and determining possible causes for the calculated results.

5.2 Analysis and Variable Comparisons

Having determined that teleoperators underperform when compared to local drivers, we now seek to understand possible reasons for the shortcomings experienced during the given tasks. In order to gain further clarity, the acquired variables are compare amongst each other in a post-hoc analysis.

The first variable to be studied is one related to a secondary hypothesis that tried to determine whether or not the camera position influences performance in the teleoperated system. To accomplish this, the performance metrics are analyzed using the previous statistical analysis. Each metric is associated to the camera position that the task was executed and subsequently scrutinized via the two-sample T-test or a Kruskal-Wallis test.

Secondly, system variables, such as the average latency and its variance, are compared to other parameters with the intent of noticing any patterns. Trends relating to the time of day are devised and interpreted as a likely source for network congestion which may contribute to decreased performance. Additionally, and due to the observed patterns, a correlation between the stops that the operators had and characteristics of the latency profile during task execution is further scrutinized and streaming video feedback as well as sending control signals is hypothesized as a cause for system strain.

5.2.1 Camera Position Analysis

As seen in CHAPTER 2, telepresence factors can, on occasion, drive operator performance within a remote control system. Based on this affirmation, the remote vehicle had two video feedback configurations; one with the camera located in front and the other with the camera positioned in the vehicle, where the drivers head would be. As a result of having two setups, a comparison between the arrangements is studied with the intent of determining whether one configuration is significantly better than the other.

To accomplish the previous, a similar approach to that used in determining the validity of the principle hypothesis is computed. That is, we first check to see whether the metrics resemble a normal distribution by means of the Kolmogorov-Smirnov test, then the variance of each sample is compared using the F-test or Levene and finally the means are compared by use of the two sample T-test or Kruskal-Wallis. If the third statistical test is rejected then the means are considered to be significantly different. This in turn would imply that one camera position helps the operator perform significantly better than the other with α at 5%.

Table 5-2 P-Values of the Statistical Test for Camera Position Comparisons, calculated as described in CHAPTER 4 (Two Sample T-test or Kruskal-Wallis Test)

	Straight Trajectory	Reverse Trajectory	Path following
Max. Dist.	0.6652	0.9803	0.3577
Total Time	0.8181	0.3548	0.2342
Area	0.8924	0.9106	0.9389
Area(Time)	0.7868	0.5162	0.0768
Max. Speed	0.8560	0.0631	0.3564
Mean Speed	0.6949	0.2183	0.4334
Stops	0.3562	0.6696	0.2488
Time Stopped	0.2289	0.2674	0.1771

Table 5-2 shows the results of the third statistical test for the metrics highlighted in the previous section, every statistical test can be seen in APPENDIX D. In the table, the first column lists the highlighted performance metric and the subsequent columns detail the p-value for the T-test, where the null hypothesis is rejected with a value lower than 0.05. It is abundantly clear that none of the statistical tests are rejected, thus implying that the means are at least significantly similar.

As a mode of example, the comparison between the camera positions for the Maximum Deviation metric for each task is shown in Figure 5-37, Figure 5-38 and Figure 5-39 in the form of boxplots, visually showing no significant difference.

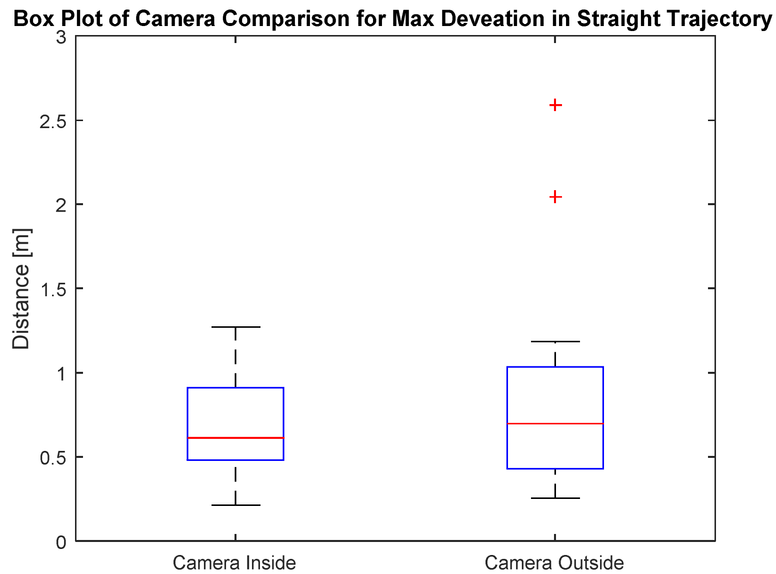

Figure 5-37 Box Plot of Camera Comparison for Maximum Distance Deviation in Straight Trajectory Tasks

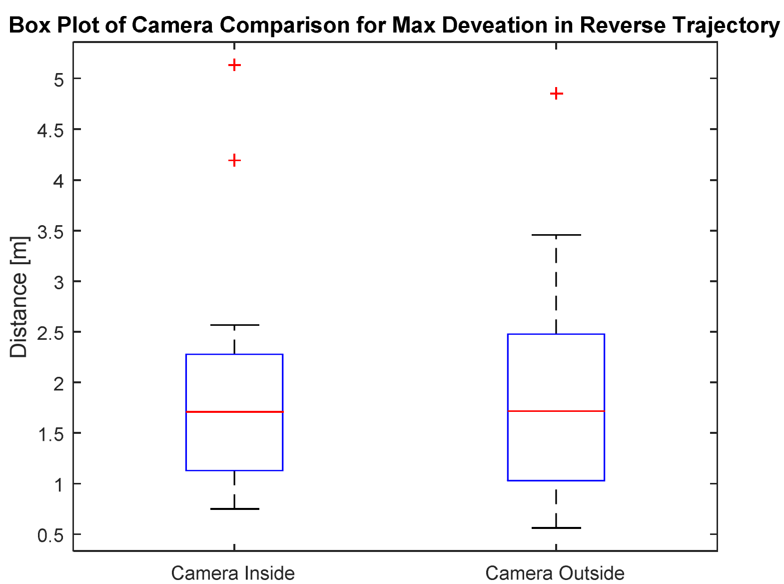

Figure 5-38 Box Plot of Camera Comparison for Maximum Distance Deviation in Reverse Trajectory Tasks

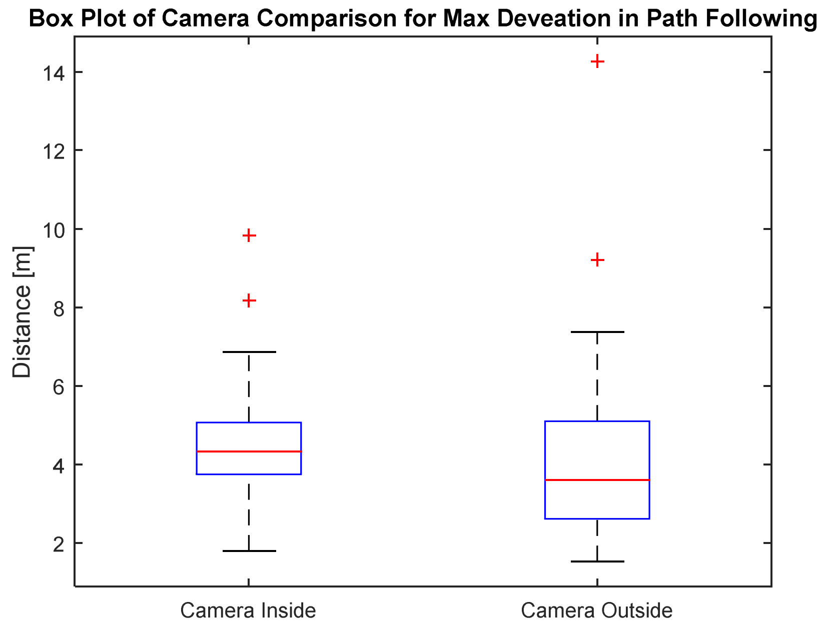

Figure 5-39 Box Plot of Camera Comparison for Maximum Distance Deviation in Reverse Trajectory Tasks

Even though there are no statistical differences in the overall metrics between one camera position and the other, individual operator improved performance is calculated and their means are tested via the previous statistical method. That is, a ratio between each metric is calculated as in eq. 5-1, where each specific performance metric PM_i is calculated with the camera located inside the cockpit and the corresponding performance metric PM_o is calculated with the camera outside the vehicle. This represents how well a task was executed respect to the camera positions, and subsequently this ratio's mean is compared to that of a normal distribution using the T-test, at a significance of α equal to 5%.

$$\eta = \frac{PM_i}{PM_o} \qquad \textit{eq. 5-1}$$

Once more, from Table 5-3, the majority of the performance metrics for a given task fail to reject the null hypothesis implying no significant difference between the means. This in turn suggests that there is no improvement between a tasks executed with a camera positioned in front when compared to the same task with a camera positioned inside the vehicle, as previously seen in the direct comparison (Figure 5-37, Figure 5-38 and Figure 5-39).

Table 5-3 P-Values of the Statistical Test for Improvement Rations in Camera Position Comparisons, calculated as described in CHAPTER 4 (Two Sample T-test)

	Straight Trajectory	Reverse Trajectory	Path following
Max. Dist.	0.4642	0.2530	0.0609
Total Time	0.8468	0.5093	0.0370
Area	0.1395	0.1633	0.2166
Area(Time)	0.2798	0.8831	0.5805
Max. Speed	0.5961	0.0119	0.2849
Mean Speed	0.6549	0.0723	0.2637
Stops	0.7481	0.5078	0.0710
Time Stopped	NaN	0.7876	0.0138

5.2.2 Latency Analysis

Another factor that is commonly associated with performance in a teleoperated system is latency. As previously stated, this parameter was compared to several performance metrics with the intent of determining if it swayed operator tasks. After comparing several metrics, two in particular present noteworthy assessments, these being the dependency of performance versus the latency and how the latency varied in function of the time of day.

A closer look at how latency compares to performance is graphically shown in Figure 5-40. Here, the information is plotted on a log-log graph in order to amplify the effect of latency over the performance metric. Though it is tempting to determine that performance is deteriorated as the latency mean increase, it is difficult to justify said assumption based off of the information presented in the figures.

Fortunately, certain conclusions can still be made from observing the scattered points. The logarithmic plots, Figure 5-39, shows each task in different colors where the straight trajectory task is shown in magenta, the reverse trajectory task is in green and the path following task is shown in blue. By visually inspecting the graph, groups of horizontal small stripe regions are recognized. This implies that particular performance metrics may be bounded to a specific area. On top of this, straight trajectory metrics are tightly grouped in the lower left side of the graph. Whereas, both reverse trajectory and path following tasks present wider bands on both latency average and variance. These two facts hint at the possibility that they are somehow forcing the system to experience higher average latencies.

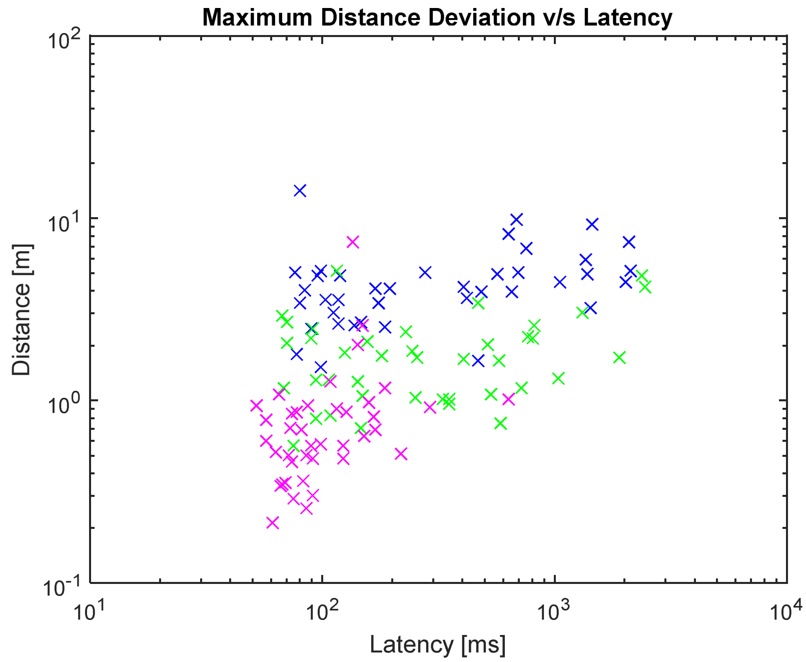

Figure 5-40 Logarithmic Plot of the Maximum Distance in Function of Latency. Blue Crosses Represent Path following Tasks, Green Crosses Represent Reverse Trajectory Tasks and Magenta Crosses Represent Straight Trajectory Tasks.

Intent on better understanding the causes for the observed latency characteristics, the study also compared the average value of latency to the time of day that each task was completed. Figure 5-41 shows the relationship that exists between these two factors using the same color scheme as illustrated in Figure 5-40.

Once more, no clear tendency is present when viewing the points scattered in one image. But when the reverse trajectory and path following tasks are plotted separately to that of the straight trajectory task, an interesting pattern arises. In Figure 5-42, the green and blue crosses which represent reverse ad path following tasks respectively, show that between 19:00 and 21:00 [h] latency tends to concentrate under the 500 [ms] mark and before 19:00 [h] the latency varies wildly, reaching values of up to 2500 [ms] averages. However, this tendency is not observed in the straight trajectory task, where latencies consistently fall under the 500 [ms] mark, as seen in Figure 5-43.

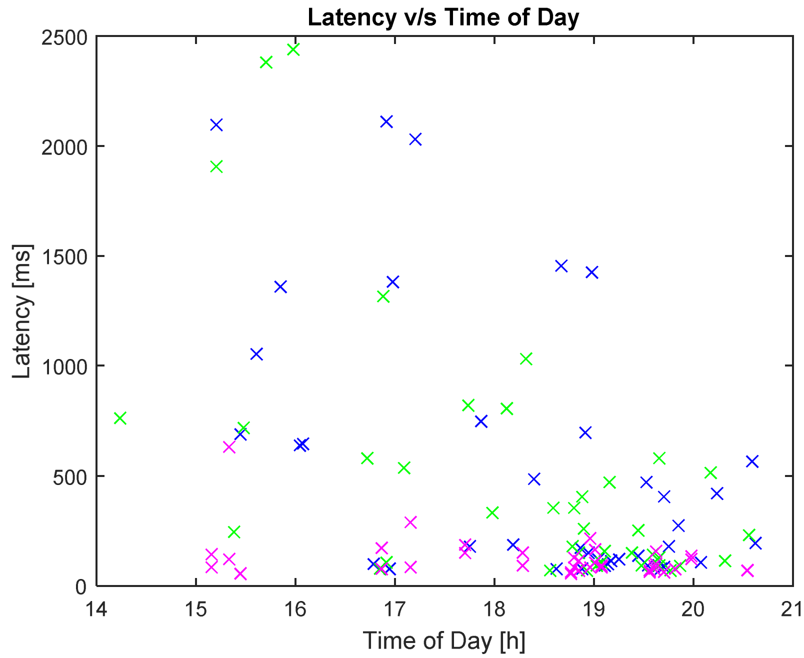

Figure 5-41 Average Latency for Each Task in Function of the Time of Day

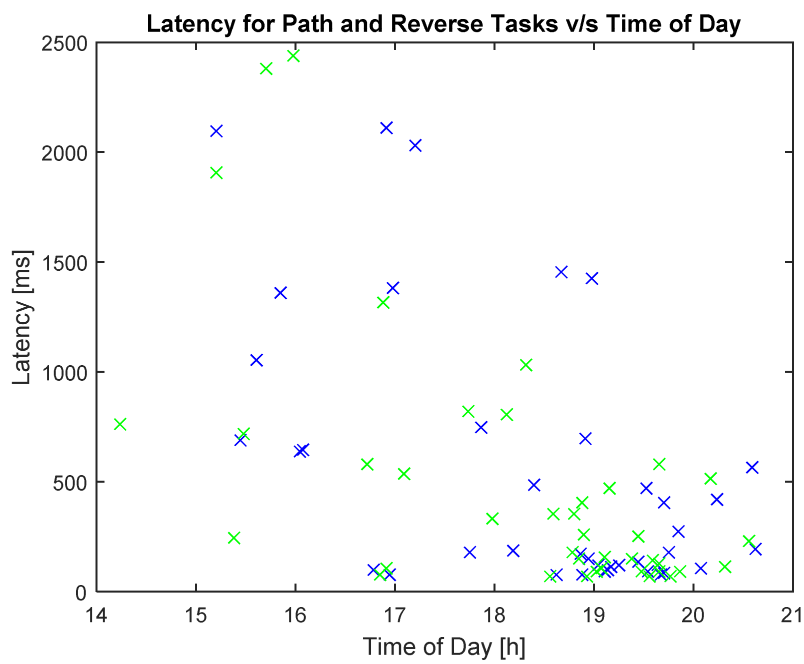

Figure 5-42 Average Latency for Path and Reverse Task in Function of the Time of Day

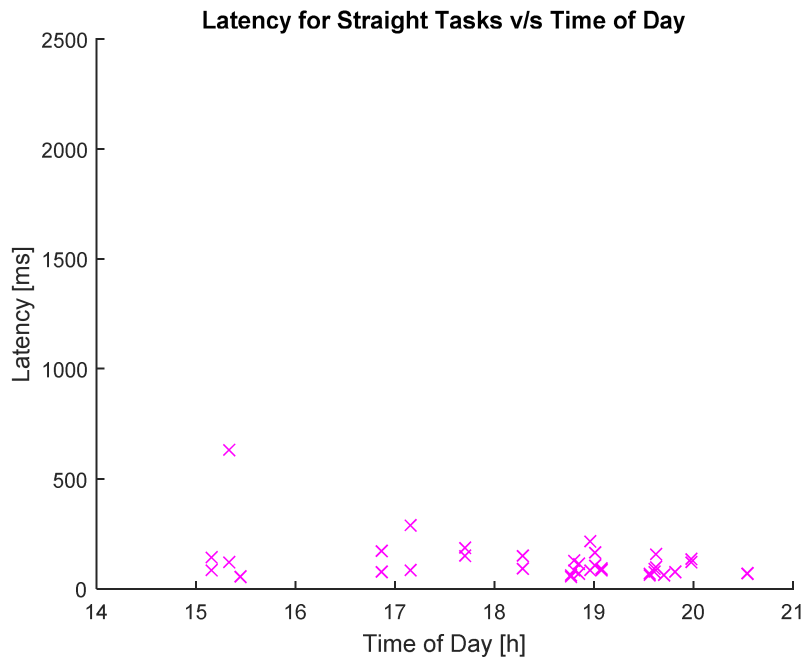

Figure 5-43 Average Latency for Straight Trajectory Task in Function of the Time of Day

Though it is not statistically proven, there seems to be a hidden relationship between latency and performance. By just comparing average latency to performance metrics, one can notice that the system reacts differently depending on the task that is being completed. For straight trajectory tasks, latencies tend to concentrate below 500 [ms] and in general have better performance metrics. On the other hand, both the reverse trajectory and the path following tasks display a higher range of latency while displaying decreased performance metrics.

Furthermore, when comparing latency to the time of day, straight trajectory tasks show less variability. However, this is not the true for both reverse trajectory and path following tasks that vary largely before 19:00 [h].

5.3 Possible Causes to the Observed System Limitations

Up to this point, an intuitive relationship between latency, performance and time of day has been established, but no underlining causes has been resolved. When focusing on the comparison between latency and performance, it was observed that straight trajectory tasks behaved differently to reverse and path following tasks. Due to this, the system latency profiles are studied in order to determine possible causes to this diverging behavior. Additionally, the latency and time of day tendencies are further analyzed and compared to network congestion statistics.

5.3.1 Latency profiles

Latency profiles for each test are computed by plotting the time delay of each control signal in function of the time the signal was sent in the corresponding run. These profiles illustrate how the time delay in the system fluctuates as the task is executed. Examples of low latency runs for each task are shown in Figure 5-44.

Though each profile provides interesting information regarding time delay in the system, its relevance becomes apparent only when other variables are overlaid and contrasted. Many of the vehicle specific parameters collected during the runs were compared to each latency profile in an attempt to recognize patterns that could help understand root causes of the variances in the system. Of all the parameters examined, two are highlighted in this study due to the implications that they provide, these being: the vehicles velocity profile and the gyroscope readings.

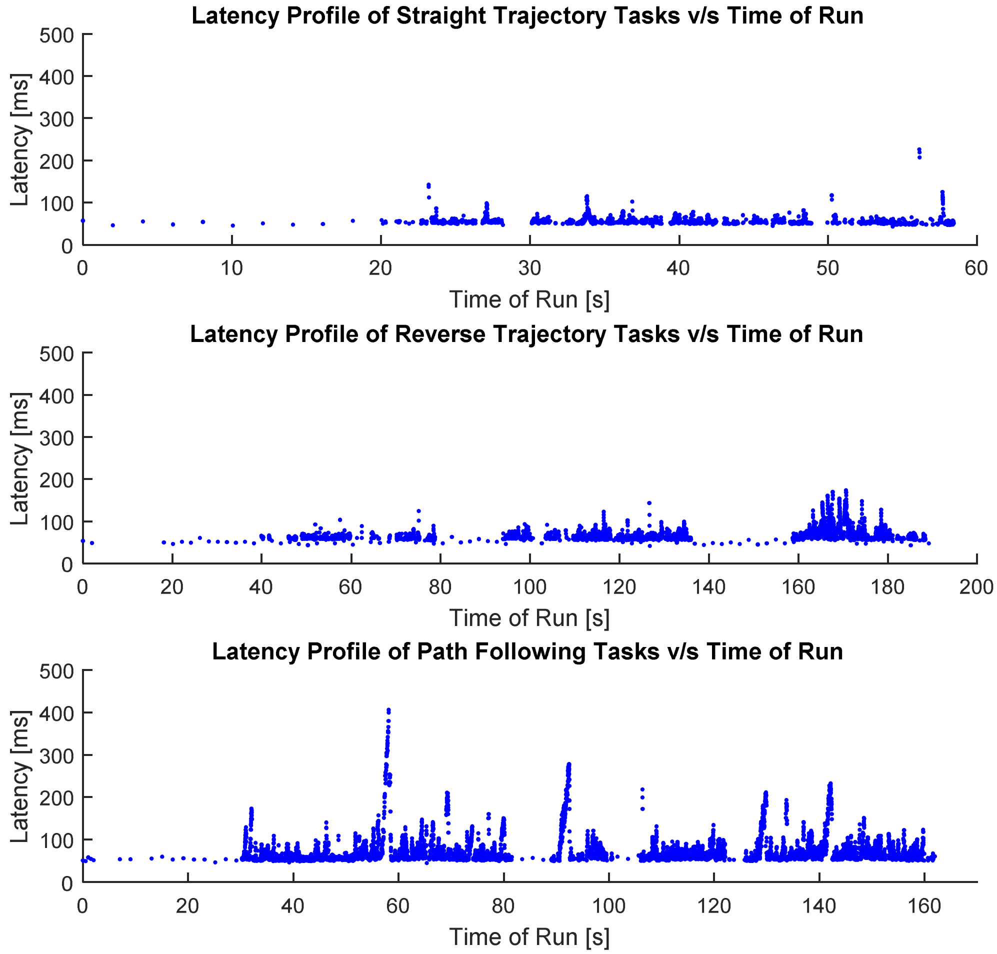

Figure 5-44 Examples of Low Latency Profiles for Each Task

In Figure 5-45 and Figure 5-46 each parameter is overlaid on the latency profile separately at first and then all together in Figure 5-47. Since the parameters being compared share no physical dimension, the y axis is set to show the value of latency and the parameters that are overlaid are scaled to an adequate size to facilitate visual inspection. The following analyses is exemplified on a reverse trajectory task for brevity, but is holds true for path following tasks as well. Just as a reminder, the reverse trajectory task consisted in driving the vehicle in reverse for approximately 20 [m] and parking. Immediately after parking the vehicle had to pull out to the left and follow a straight line for less than 20 [m] and stop on a marker.

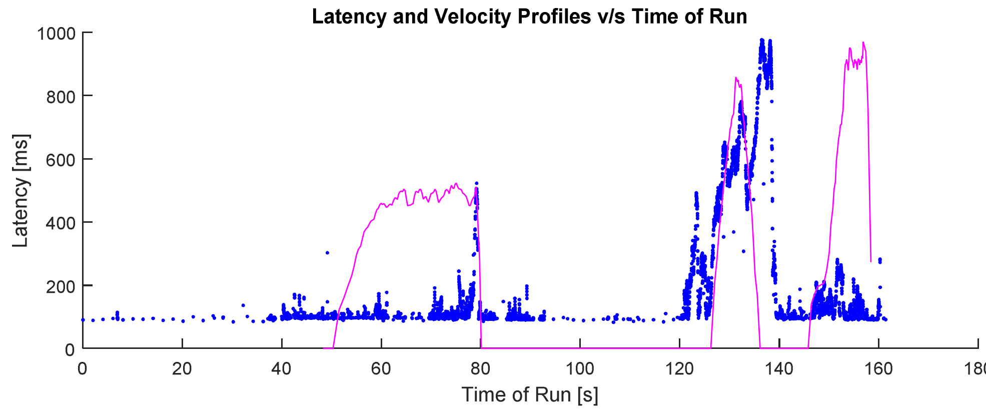

Figure 5-45 Latency and Velocity Profiles in Function of Time of Run. Latency Profile is shown in Blue, Velocity Profile is shown in Magenta.

From Figure 5-45, where the latency is compared to the velocity profile, one can infer that initially the vehicle is stopped and consequently the latency profile is relatively stable. However, when the vehicle starts to backup, small fluctuations in latency appear and slowly start to gain prevalence. Before the car's first stop, at around the 80 second mark, we notice a small spike in the latency but it subside quickly after the vehicle comes to a halt. During the period that the vehicle is stopped, between the 80 and 120 second marks, the latency profile appears to stay stable. But as soon as the cart starts to move again, almost immediately the system latency starts to spike to levels that are unsustainable for teleoperation. Therefore the operator stops the vehicle and lets the system stabilize, close to the 140 second mark. Once the latency appears to be stable again, the vehicle starts and ultimately concludes the reverse trajectory task at the 160 second mark.

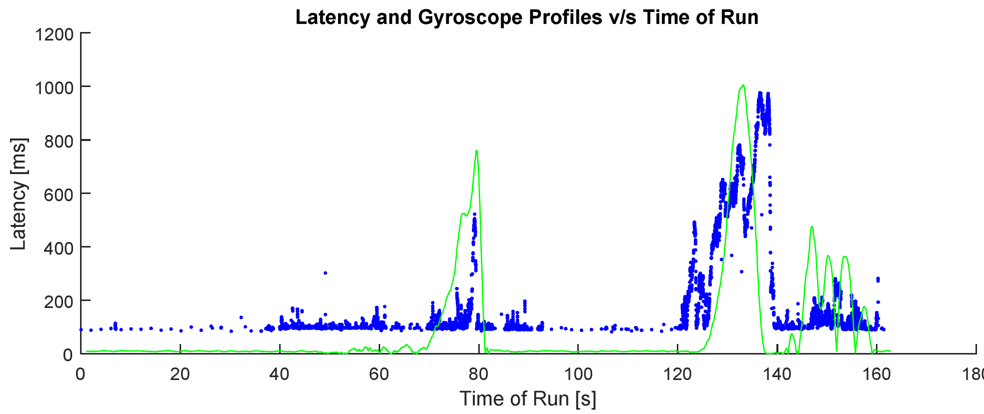

Figure 5-46 Latency and Gyroscope Profiles in Function of Time of Run. Latency Profile is shown in Blue, Gyroscope Profile is shown in Green.

Turning our attention to the gyroscope readings, the values are overlaid on the latency profile as shown in Figure 5-46. In this case, one can notice that at the beginning of the run, the gyro is at rest and analogously the latency reading remain stable. Soon after, at around the 40 second mark, the latency starts to display small perturbations but nothing significant until the gyroscope detects that the vehicle starts to turn, close to the 70 second mark, and almost immediately there is a spike in latency. After the vehicle stops turning, latency values return to normal and remain there until the sensor detects rotations again, displaying this characteristic latency behavior all the way until the end of the run.

By combining both variables over the latency profile, as seen in Figure 5-47, one starts to notice that variances in latency loosely follow the velocity and gyroscope profiles. Better understanding what these parameters measure we see that the first metric, velocity, quantifies the linear speed that the vehicle is subjects to. Similarly, the gyro parameter quantifies the angular velocity that the vehicle has.

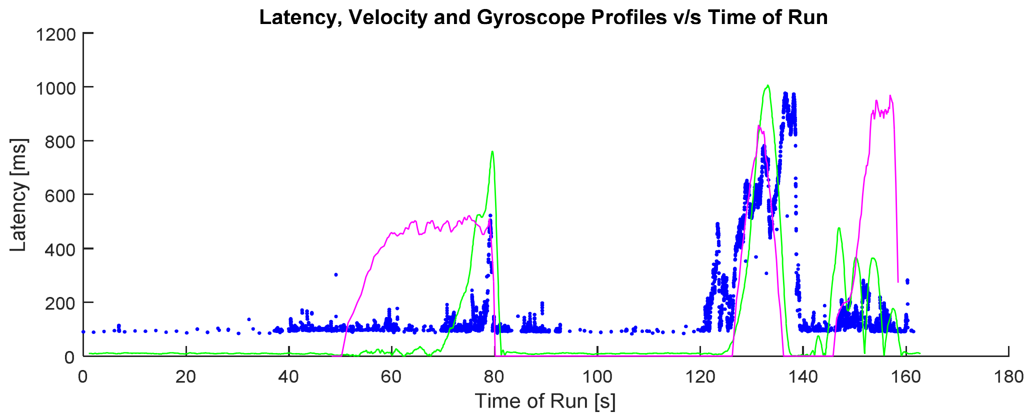

Figure 5-47 Latency, Velocity and Gyroscope Profiles in Function of Time of Run. Latency Profile is shown in Blue, Velocity Profile is shown in Magenta, and Gyroscope Profile is shown in Green.

But the question still remains, why is latency affected by these velocity metrics? It is here that this study believes that the underlining cause of variance in the system is not cause by actual velocity, but rather what happens when the vehicle is in movement. Going back to the basics, the teleoperation system is setup so that control signals flow from the operator station to the vehicle and simultaneously, the vehicle is streaming video feedback to the control station. When the vehicle is idle, the cameras are streaming a constant image that, due to encoder algorithms, is compressed significantly resulting in low bandwidth utilization. As the vehicle starts to pick up speed, the cameras start to process scenery changes which in turn force the compression algorithm to start to send more information over the internet connection. However, as seen in the latency profile when the vehicle moves in a straight line, though the scenery is changing, the majority remains the same and no significant strain is placed on the cellular network. It is only when the cart starts to turn and significant changes to the scenery take place along with a jump in control signal being sent, that large variances to the latency profiles become apparent. Therefore, this study believes that the underlying cause to variability in the latency may be consequence of limitations in the bandwidth due to spikes in video streaming and control signals being sent through the network.

Though rapid changes in scenery look like a probable candidate to system complications, one would expect to observe these effects throughout every test, independent of the time of day the tasks is executed. Nevertheless, this is not the case, and the system is capable of performing on par under certain circumstances, as seen in Figure 5-42 that compares latency to the time of day that the task was completed. Therefore another cause must exist that in conjunction with video and data stream strains, cause the system to underperform.

5.3.2 Network congestion and Time of Day

A previous image, Figure 5-43, illustrated an interesting correlation between latency and the time of day. Here, one could identify that straight trajectory tasks displayed little dependence to the time of day. According to the previous assumptions, a probable cause for the low variability behavior now exists. That is, since the straight trajectory tasks presents little change in the scenery and almost no significant control signal requirements, then video and data streams exerts little strain on the system.

Nevertheless, if this hypothesis were the only cause for this behavior, then it would also be present in Figure 5-42. In other words, one would expect to see large latency variability independent of the time. However, a clear tendency of reduced latency is detected after 19:00 [h].This leads this study to believe that intrinsic challenges related to load on the network also affect system latency.

Investigating typical loads on cellular networks, (Son, 2011) collected and normalized demand on a cell tower located in an urban setting. Figure 5-48 shows how demand swings widely from high network demand during the day to minimal demand during the night. Critical points in time are after 18:00 [h] in the morning when network activity picks up and after 18:00 [h] at night when activity starts to subside. Comparing this information to the conclusions extracted form Figure 5-41, a reasonable inference can be made that when high network demand is present in the system then larger variances may be expected. Similarly, if the cell tower is under less demand, commonly present after 19:00 [h], then the system will behave in a more stable manner.

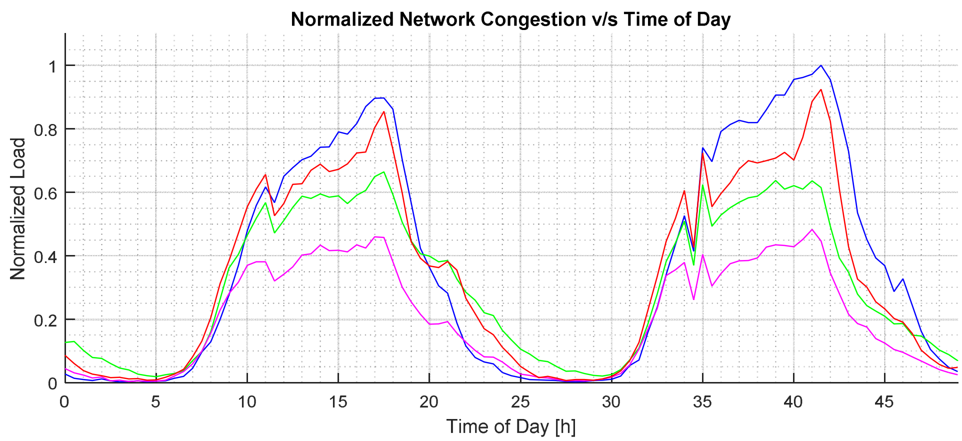

Figure 5-48 Normalized Network Congestion in Function of Time of Day in an Urban Setting. *(Son, 2011)*[1]

Taking the previous assumption into account and contrasting them to the hypothesis that the video and data streams affects system performance, this investigation believes that all these factor have a compounding detrimental effect over the teleoperation system. To better explain this, consider the following analogy of water flowing through a pipe. In this case, water represents the amount of information being sent by the video and data streams to the control station, and the diameter of the pipe is analogous to the bandwidth of the network. Hence, the amount of water that needs to be sent over the pipe will vary depending on the amount of information that is being sent over the network. If the vehicle needs to turn the then data stream starts to utilize more

[1] This data was obtained from experiments conducted by the University of Southern California's Autonomous Networks Research Group, http://anrg.usc.edu.

bandwidth as will the rapid changes in scenery, analogously more water needs to be sent through the pipe. If the pipe is large enough, then it doesn't matter if the water flow is large or small, because the pipe can handle the flow. But if the pipe diameter is not large enough, which might be due to network congestion, then the flow through the pipe will reach a maximum and water will start to accumulate at the entrance. This accumulation of water at the entrance can in turn be understood as latency.

5.4 A Posteriori Analysis

Though this study believes that the main cause of underperformance in the system is attributed to network congestion and variability in data streams, which ultimately result in variable latencies; it is hard to quantify the individual effects that each subsystem has on the overall performance of the participant. A comparative study between the camera positions was shown in section 5.2.1; showing that even though participants overwhelmingly believed that the camera position affected their performance, when reviewing the statistical comparison, no significant difference could be seen. Though, it's not to say that it didn't actually hinder their individual performance in other ways than accounted for in this work.

The teleoperated system has many interlinking subsystems that can affect user performance differently. And if properly accounted for, insight into these could ultimately provide clearer paths to improving cellular teleoperation, without having to alter the underlying constraints discussed in CHAPTER 3. Subsystems that can influence performance are: the Graphical User Interface (GUI) that shows the operator the remote environment and allow them to visually interpret how events are transpiring; the supplementary information that is displayed to the operator (like current speed, LIDAR or GPS), where on top of aiding the decision process, the information also utilizes bandwidth and can ultimately cause more difficulties that what it helps; the amount of cameras simultaneously streaming and the incremental information they provide the user; where they ultimately use more bandwidth but provide a wider camera angle, the question here might be to develop a trade-off between the field of view versus bandwidth utilization; or even the human element and variability to latency introduced by experience and reaction time. All these elements, and more, play a vital role in improving operator performance but were not duly collected so as to be able to objectively infer conclusions from them. However, some comments can be provided based on experience collected throughout several of the experiments conducted.

An interesting subsystem that proved to introduce more variability than expected was the rear camera view. The effects that spawned from this were twofold: 1- where the actual display seemed to block the front view camera and 2- the view provided cause some operators to turn in the wrong direction. When displaying the rear camera view, it was overlaid in the bottom right corner of the front camera view and some participants commented that this seemed to distract them when driving and believed that it could either be placed on another screen that was used less than the front view or appear only when it was needed. Furthermore roughly 50% of the operators were disoriented when driving the vehicle in reverse and believed that the image should be flipped vertically, representing more of a mirror image similar to when looking in a rear view mirror.

The initialization time when switching between cameras sometimes took several seconds. Though this does not directly affect many performance metrics, it did prolong the amount of time the operators were stopped and sometimes provided uncertainty as to whether the camera stream would actually appear. However, when discussing this issue, many drivers did not seem to mind the length of time to initialize the camera and some welcomed it, because it left them time to rest before starting to drive again.

One point that the majority of the participants commented on was that they preferred having the camera positioned inside the vehicle as opposed to having it outside. When asked to further explain their preference, several participants stated that it was because they could better estimate the amount of latency in the system by measuring when they moved the steering wheel and estimate the amount of time that lapsed before they saw a response on the remote environment. Though no statistically significant difference was measured in performance due to camera positions, this could eventually improve performance due to an increased confidence in predicting how the system will react to any input they provide.

An interesting revelation was made apparent, after all the experiments were concluded, while trying to determine the bandwidth used by different factors in the system. It was seen that under certain circumstances, video streams could use anywhere between 0.5 [Mbps] and 3 [Mbps] depending on the quality and variability in scenery. Furthermore, it was expected that the control stream would use under 0.5 [Mbps]. However, when measuring the through put of the control signals, it was observed that they used approximately 1 [Mbps], significantly more than expected. This further suggested that the strains in the system could be due too much information trying to be sent over the network.

Finally, an interesting study that may ensue in future works would have been to be able to determine the incremental amount of information that was relayed to the operator due to specific auxiliary feedback. In other words, it would be interesting to see if one could quantify how much information is being captured and used by the operator based on the amount of data that these factors use in the available bandwidth. For example, does the amount of information used by relaying the current speed that the vehicle has improve the overall performance of the operator compared to the strain it has on the network, furthermore are their other factors that could be included to improve the users awareness that do not impose a significant strain on the network. Unfortunately, the methodology implemented in this work didn't account for individual testing of these parameters and thus cannot be objectively quantified. However, it is the belief of the author that they did not influence the operator due to the heavy fluctuations in latency and video quality the drivers experienced.

5.5 Summary

Recapping, before the results and statistical analyzes were presented, a description of every performance metric was thoroughly detailed, grouping them into 3 main categories: 1- Trajectory Performance Metrics, 2- Control Signals Performance Metrics, and 3- System Variables Performance Metrics. In total, 20 metrics form the basis off of which the validity of the principle hypothesis is tested. Though 20 metrics are detailed, only 10 are highlighted in the results and statistical analysis section since they help provide a clearer image of how the operator performs.

Concluding the preamble of the performance metrics, the thick of this work is presented in the results and statistical analysis section. Performance metrics for each of the three tasks are shown by means of boxplots and compared to its corresponding ground truth. Each of the performance metrics are submitted to a three stage statistical analysis and the results are detailed along with a brief description of their significance. It was seen that for all three tasks, the performance of the operators did not meet expectations. Specifically, in the straight trajectory tasks 13 of the 20 performance metrics rejected the statistical tests; in the Reverse Trajectory Tasks 17 of the 20 metrics rejected the statistical tests; and in the Path Following Tasks 19 of 20 metrics rejected the statistical tests. On top of determining that operator performance underperformed and thus the validity of the principle hypothesis was rejected, certain factors hint at underlying difficulties, like high number of stops and oddity in the average and standard deviation of latency, that are further explored later in this chapter. Nonetheless, some more experienced drivers were able to perform just as well as in-situ drivers hinting that if system conditions are nominal, then optimal performance is achievable.

Subsequently, results to the questionnaire are detailed and categorized into four groups: Camera Location Comparison, Video Feedback, System Latency Levels and Overall Perceived Performance. Regarding the Camera Location Comparison, it was seen that user overwhelmingly prefered the camera positioned inside the vehicle even though it was statistically proven that camera position had little effect on overall performance. For Video Feedback it appears that users experience more quality related issues, nevertheless the overwhelming majority believed that improving frames per second would be most helpful. In the System Latency Levels the operators no clear tendency was shown, however when reviewing latency profiles it is clear that latency is present in the runs. And for Overall Perceived Performance, it was interesting seeing that most users believe that they performed relatively well, and that they believed that what most hindered performance was time delay.

Though it was shown that the principle hypothesis was rejected, this study delves into possible causes for the calculated results. Variance sources due to camera positioning and latency are studied. Analyzing performance in function of the camera position, it was seen that no statistical difference existed between the metrics. Furthermore, no improvement was perceived due to changes in camera position. On the other hand, significant variation can be attributed to latency, like stratification in performance metrics. On top of this, certain patterns emerge regarding time of day that are later shown to affect latency and consequently overall performance.

Lastly, latency profiles and network congestion are hypothesized as the principle bottles necks to the teleoperated system. The latency profiles are compared to several system variables, and an interesting relationship is found to involve velocity parameters. Also, network congestion is found to be cyclical and coincide with variability of the average latency values when compared to the time of day. Taking both of these factors into account, latency profiles and network congestion, this work believes that they conduce to “blockage” in the channels and ultimately reduce available bandwidth availability to operations involving high use of video and data streams.

CHAPTER 6

CONCLUSIONS

In this work, a cellular teleoperated system was built and tested. Its main objective was to determine the validity of the hypothesis "A vehicle can be controlled over a 4G LTE network streaming HD video feedback" through means of statistical analysis. After several tests, the hypothesis was overwhelmingly rejected and insight into what and why the system presented issues were discussed.

In what is left of this thesis, a summary of the information detailed heretofore will be reviewed along with relevant conclusions pertain to the completed experiments. Finally, future works related to this investigation and how cellular teleoperation may be improved are discussed.

6.1 Summary

Clearly teleoperation has grown at huge steps spanning across many disciplines and science fields. On top of this, each field has seemingly unbounded space to continue growing. One field that is of particular interest to this study is the communications medium that the teleoperated system uses, that is, cellular networks. For decades, cellular communication has consistently increased data transfer rates and mobile access while decreasing latencies. This has happened to such an extent that it is now possible to stream large amounts of data which in turn allows for exploring new uses such as teleoperation (Ericsson, 2015).

Due to this new found ability to stream enough feedback to the operator and have him control a remote environment, this study found it necessary to test the actual capabilities of commercial cellular networks and determine if they offer reliable services to the extent that they allow for “a vehicle to be controlled over a 4G LTE network streaming HD video feedback”, this works principle hypothesis.

In an attempt to determine the validity of the hypothesis, a review of what teleoperation is and current industry uses are described. It was seen that teleoperation can be grouped into 5 categories; 1- Master-Slave, 2- Supervisory-Subordinate, 3- Partner-Partner, 4- Teacher-Learner and 5- Fully Autonomous. Furthermore, uses for it span across a plethora of industries, like; space exploration, military or defense, removing humans from toxic of hazardous environment, or even medicine where long distance and micro surgeries are made possible.

Current research standards for quantifying the performance of a teleoperation system are elaborated on. Time and frequency domain analysis dominate control systems quantification strategies, while other more holistic approaches measure user performance of overall task completion, such as deviation from path or total time of task execution.

To better understand the main limitations present in cellular based teleoperation, internet based time delay is explained. Packet switched networks are presented as sources of latency and benefits and disadvantages of UDP and TCP protocols are detailed. Also, different wireless communication methods, i.e. Bluetooth, Wi-Fi, etc., are compared side by side, highlighting different characteristics.

On top of this, current investigations that delve into cellular based teleoperations are described, highlighting strengths and weaknesses encountered in both methods and results. The earliest investigation to delve into cellular teleoperation (Gnatzig, Chucholowski, Tang, & Lienkamp, 2013) constructs a simple system that controls a small robotic vehicle. Their main concerns are data rates and latencies and thus base their success on achieving comparable results in transfer rates and time delays. They ultimately conclude that while cellular teleoperation is possible, it comes with difficulties.

Subsequently, (Munoz, Eusse, & Cruz, 2007) and (Shen, et al., 2016) both implement cellular teleoperation on commercial vehicles and test the systems by measuring transfer rates and latencies and determine that cellular teleoperation is possible. However, most of their final remarks highlight that properties inherent to cellular networks should be studied to allow for improved teleoperation.

Presenting the preamble and getting acquainted with current research, this thesis proceeds to describe how this investigations teleoperation system is setup and highlights relevant characteristics. This works teleoperation architecture is a master-slave configuration with minimal autonomous algorithms incorporated on the remote side for safety reasons. Both operator station and remote environment are programed in a web browser environment due to the advantages of using webRTC in conjunction with STUN/TURN servers. Lastly, both operator and remote environments are detailed and key characteristics, such as camera configurations and instruments, are described.

Following the system description, the experimental design and statistical analysis principles are presented. A detailed explanation is given of why this investigation chose 3 principle tasks to be conducted during the experimentation phase. Along with objectives that each operator needs to achieve in order to successfully complete each task. Insight is given into how the required variables used in the posterior analysis are collected and calculated, and the statistical tests and criteria are presented.

Ultimately, the statistical tests try to determine the validity of the principal hypothesis. To accomplish this, the variables collected and calculated from the experiments are subject to a three stage statistical test whose final goal is to compare the average value of teleoperation performance to ground truths. If the statistical tests do not reject the null hypothesis, then it can be said that the means are significantly similar and thus the teleoperation system performance can be said to be comparable to a local driver present in the vehicle. Otherwise, if the tests reject the null hypothesis, then the means are not similar and the teleoperation system performance is not similar to in-situ driving.

The three stage statistical test checks for normality in the first stage by performing a Kolmogorov-Smirnov test. Depending on the results of the first test, the second stage compares the variance of the experimental data to the ground truths using either an F-test or Levene test. In the third stage, the means of the experimental data are compared to ground truths via a two-sample T-test or a Kruskal-Wallis test and, aggregating the information of all test, the principle hypothesis validity is determine.

Understanding how the system is built, how this investigation plans to measure performance and what statistical tests will be used to complete the analysis, the experiments are conducted and results detailed. In the experimentation phase, 20 participants complete each of the 3 tasks 2 times with different camera positions in each iteration. From the previous, several variables are collected, calculated and performance metrics are determined. After this, the results are compiled and shown in Chapter 5. The statistical results to each task are detailed separately so as to better understand how performance varies according to each task. Briefly, each task: straight trajectory tasks, reverse trajectory tasks and path following tasks, overwhelmingly show that remote operator performance is significantly different to in-situ drivers and generally underperforms. However, in some cases, more experienced drivers were able to perform on par with in-situ drivers.

In an attempt to recognize possible causes to the results obtained, a comparison between camera location and user performance is completed. The same statistical procedures used to determine the initial hypothesis is performed on a secondary hypothesis that postulates "the camera positions have a significant effect on performance when teleoperating a vehicle". The results to this analysis show no significant difference between the means and thus lead this investigation to conclude camera position does not influence operator performance. Hence other sources of variance are studied in hopes of identifying bottlenecks in the system. From this, two main factors are thought to contribute to reduced performance: network congestion and variability of bandwidth utilization.

By the end of Chapter 5 an attempt to explain what this investigation believes is that principle cause of reduced performance is made via an analogy of water flowing through a pipe. Water represents the amount of information being sent by the video and data streams to the control station, and the diameter of the pipe is analogous to the bandwidth of the network. Hence, the amount of water that needs to be sent over the pipe will vary depending on the amount of information that is being sent over the network. If the vehicle needs to turn the then data stream starts to utilize more bandwidth as will the rapid changes in scenery, analogously more water needs to be sent through the pipe. If the pipe is large enough, then it doesn't matter if the water flow is large or small, because the pipe can handle the flow. But if the pipe diameter is not large enough, which might be due to network congestion, then the flow through the pipe will reach a maximum and water will start to accumulate at the entrance. This accumulation of water at the entrance can in turn be understood as latency.

Ultimately, this investigation works through the nuances of explaining the state of art of cellular teleoperation. It details the configuration of the system used and the method to statistically validate the principle hypothesis. Experimentation is completed in order to determine if the cellular teleoperated system is on par with in-situ driving. After processing the collected information and computing results, and though some operators were able to perform optimally, the main hypothesis "A vehicle can be controlled over a 4G LTE network streaming HD video feedback" is rejected and possible complications are explored.

6.2 Achievements

Having summarized the work accomplished in this investigation, a list of achievements is given. The achievements are grouped into 4 subdivisions: 1) motivation and state of art, 2) system description and experimental design, 3) experiments and results, and 4) analysis of results.

6.2.1 Motivation and State of Art

In the subdivision, achievements that highlight why this investigation takes place and what has already been done are given.

- A need for measuring the efficacy of cellular teleoperated systems is established due to the breakthroughs in cellular transfer rates and ubiquity of coverage areas.
- The state of art of cellular teleoperation is investigated and common methods for measuring system performance are outlined. Even though the common method of performance quantification is to measure system level variables, such as time delay and throughput, this research uses an alternative method to quantify performance in a more holistic point of view.

6.2.2 System Description and Experimental Design

Specific achievements that highlight accomplishments relating to how the system is built and how this work designed the experiments to validate the principle hypothesis, “a vehicle can be controlled over a 4G LTE network streaming HD video feedback”, are given.

- A master-slave internet based teleoperated system is built, implementing minimal autonomous algorithms on the remote environment for safety reasons.
- Network address translation (NAT) is achieved using commercially available products that conveniently allow the use of web based API’s, such as webRTC.
- Tasks that reflect real world difficulties while driving are established and data acquisition methods are implemented. The tasks are:
    - Straight trajectory tasks: drive the vehicle in a straight line as fast as possible and stop on a given physical checkpoint.
    - Reverse trajectory tasks: drive the vehicle in reverse and park in reverse. Subsequently the driver must pull out of the parking spot to the left and drive to the final checkpoint.
    - Path following tasks: the driver must drive along a given path that requires him to pass over 2 checkpoints while turning to the left and park the vehicle in a parking spot. The driver must then pull out in reverse and park in reverse. Finally, the driver must pass over two more checkpoints and stop on the last checkpoint.
- A three stage statistical test method is detailed and used for determining the validity of this works principle hypothesis. The stages of the test are:
    - Determining normality: first, the normality of the performance metrics are determined. This is done so that the proper test can be selected in the

subsequent stages, i.e. parametric or non-parametric statistical testing. A Kolmogorov-Smirnov test is used for testing Normality.

- Comparing variance of the performance metrics to ground truths: A comparison of variance between teleoperation and in-situ driving is performed. Depending on whether the performance metrics was deemed to be normal or not, an F-test (parametric) or a Levene test (less sensitive) is performed.
- Comparing means of the performance metrics to the ground truths: A comparison of the means between teleoperation and in-situ driving is performed. Depending on whether the performance metrics was deemed to be normal or not, a tow sample T-test (parametric) or a Kruskal-Wallis test (non-parametric) is performed.

6.2.3 Experiments and Results

The core of the work performed in this thesis is shown in the results section. Important achievements highlighted from the compiled results are listed herein.

- Over 5 hours of continuous teleoperation are logged by 20 participants completing a total of 120 runs.
- Results of the statistical testing of the Straight trajectory Tasks:
  - The principle hypothesis is rejected, where 13 of a total of 20 metrics fail to meet statistically significant similarity to ground truth values.
  - Nevertheless, in some cases high performing drivers did approximate values seen in ground truths.
- Results of the statistical testing of the Reverse Trajectory Tasks:
  - The principle hypothesis is rejected by 17 of a total of 20 metrics.

- As in the Straight Trajectory Tasks, some high performing operators are able to emulate in-situ driving characteristics.
- Contrary to the previous task, an abnormally high number of stops are observed. This is further studied and is a contributing factor in assuming that the video stream may cause reduced teleoperation performance.

- Results of the statistical testing of the Path Following tasks:
  - The principle hypothesis is rejected by 19 of a total of 20 metrics.
  - As in the Reverse Trajectory Tasks, some high performing operators are able to emulate in-situ driving characteristics.
  - Similar to the previous task, an abnormally high number of stops are observed.

- Specific insight gained by analyzing the response that the operators provided in the questionnaire are listed herein:
  - It was seen that users overwhelmingly preferred driving with the camera positioned on the inside due to the feedback of current cockpit conditions that it relayed to the operators.
  - A majority of the users believe that they experienced video quality issues that heavily affected their performance, and of the issues they proclaimed that the low frame rate most affected their experience.
  - Pertaining to perceived time delay, a majority of the operators believed that a high time delay existed and affected their performance. On the other hand, to a lesser degree, some operator seemed to not experience a time daily that they believed affected their driving ability.
  - Finally, regarding overall performance, the majority believed they performed close to adequate, while the principle issue that they believed most affected their performance was time delay.

6.2.4 Analysis of Results

As important as computing results and rejecting the principle hypothesis, finding possible root causes to why the given performance was witnessed, is paramount. The analysis of the results is presented in the second half of chapter 5 and important achievements extracted from this chapter are highlighted here.

- Tring to elucidate probable causes for the reduced performance encountered in this investigation, performance metrics categorized by the camera position were analyzed. It was found that no statistical difference in the performance metrics between camera positions exists. Thus ruling out variance due to camera position.
- It was seen that the time of day played a significant factor in average latency for the more complicated tasks, Reverse Trajectory and Path following.
- Though not statistically proven, more complex tasks displayed higher average latencies. That is, Path Following tasks had a higher average latency than Reverse Trajectory Tasks. And analogously, Reverse Trajectory Tasks showed higher latencies that Straight Trajectory Tasks.
- Latency profiles for each task are studied and a correlation between scenery changes and latency spikes is hypothesized, but not statistically proven.
- It is believed that the main cause of the reduced performance observed in the teleoperations system is due to a mix of network congestion coupled with the variability of video and data strain on the cellular communications backbone.

6.3 Future work

In a way, statistically showing that the cellular teleoperated system is not up to par with in–situ drivers shows that there is only room for improvement. This is good on several more levels because it allows for new methods and ideas to flourish, ultimately pushing researchers to investigate new ways of achieving tasks previously unthought-of. In an attempt to guide future works that may seek to implement a cellular teleoperated system, possible research avenues are listed.

As seen in this research, several fronts of investigation are open to further development. Among the most important, according to this authors view, are 3 fundamental areas of study: predicting network congestion, predicting loss of connection and allowing parallel connections or implementing connection redundancies.

6.3.1 Predicting Congestion

By the end of chapter five, it has become increasingly clear that the quality of video streaming and overall system latency depend on how congested the cellular network is. Unfortunately, the teleoperated system has no control over the amount of people connecting to the cellular network. Notwithstanding, it is the belief of this research that if one could know actual bandwidth restrictions, then preventive measure could be taken so as to reduce strain on the system by limiting bandwidth.

By limiting the maximum bandwidth used, it is expected that the latency in the system would tend to decrease. By decreasing the time delay in the system, then the users should feel that the remote environment is more responsive to their stimuli and thus improve user performance metrics.

This line of investigation brings forth two fundamental issues so as to properly implement; 1- how to effectively predict network congestion and 2- what signal should be throttled to minimize bandwidth use while maximizing user performance.

Both lines of research pose significant difficulties due to the nature of what is being investigated. However, if successfully implemented, they may allow for enhanced performance for longer periods of time over any cellular network.

6.3.2 Predicting Loss of Connection

While congestion is an important issue that should be addressed to improve operator performance. A more significant threat to systems stability is a loss of connection with the remote environment. Though this condition rarely happens when teleoperating over a cellular network, and in this investigations tests it did not occur, it is a matter that poses important consequences. Predicting real-time connection loss is a difficult task and, to the knowledge of this author, no particular algorithm exists capable of such feat. However approximations do exist.

This topic, too, has two central points that must be studied in order to achieve proper implementation; 1- predicting actual connection loss and 2- autonomous control algorithm that handle the vehicle after loss of connection is detected.

Regarding the connection loss research area, real time implementation of this is relative to what is understood as real time. In other words how fast does the algorithm have to detect that the operator station is no longer receiving or sending information. This is a difficult question and determining any valuable metric may be even harder, due to the variable nature of an internet connection. However it is vital for safe implementation of any teleoperation system.

Secondly, what should be done when connection loss is detected? This may not be as complex as the previous obstacle due to recent advances in autonomous vehicles. Nevertheless, questions regarding the nature and extent of autonomous algorithm implementation should be studied.

6.3.3 Parallel Connections or Redundancies

Finally, one of the last lines of research that can be investigated in hopes of improving the cellular teleoperated system is how to maintain a parallel or redundant connection. Thought these two concepts are shown together, they are far from it and both can be implemented simultaneously or separately having different effects on overall system performance.

Implementing redundancies in the system would be aimed at trying to reduce connection losses by having a backup system on standby. Though this may seem like a straight forward implementation, in practice it is much more complicated to achieve optimal implementations due to the significant initialization time for the system to come back online. Work in this area would be focused on understanding when a connection loss is possible and how to reduce the initialization time of the standby system so that minimal control loss is experienced.

On the other hand, parallel connections aim to virtually decrease bandwidth constraint on the system by adding a second pipeline for data to flow through. Here, data and video channels could be separated and routed through different cellular modems. This would effectively reduce the amount of information being streamed through the each pipeline in the system during high bandwidth consumptions, like steering the vehicle and fast scenery changes, ultimately improving driver performance of the teleoperated system.

APPENDIX A

TELEOPERATION SYSTEM

NODE AND INFORMATION FLOW

DESCRIPTION

The teleoperation system, as described in CHAPTER 3, is made up of several nodes and information flows. These are described in Section 3.2 of CHAPTER 3, but shall be further detailed here. In other words, this appendix further details the content of the information in each flow line in Figure A-1 along with providing descriptions of each control node. Furthermore, a list of all variables available in each flow line is shown in Table A-1. Lastly, Table A-2 details the make and model of all relevant hardware included in the project.

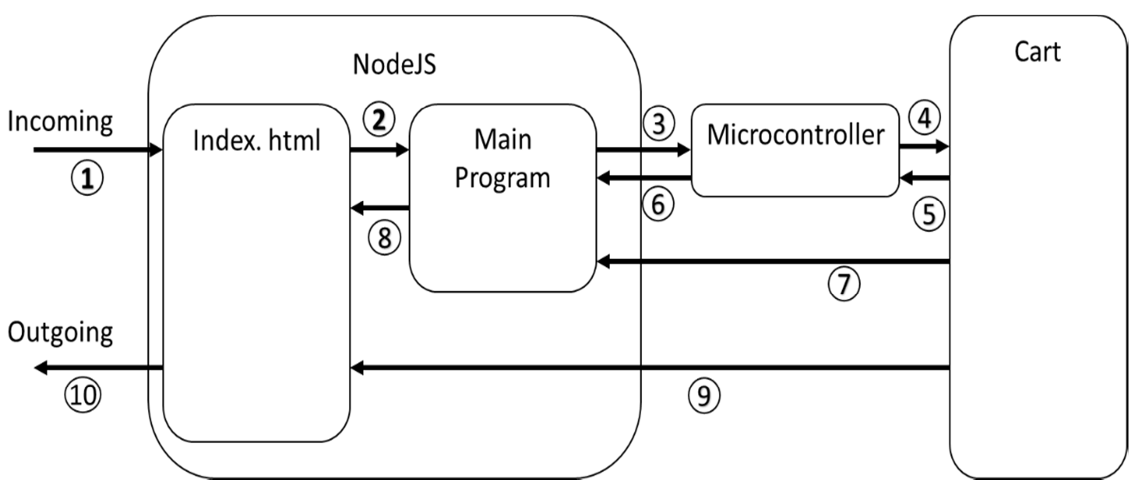

Figure A-1 Remote Vehicle Control Nodes and Information Flow

- **Remote Vehicle Information flow:**
  - **Incoming, line 1:** The incoming signals are all those necessary to control the vehicle. These signals come into the server in an asynchronous fashion and are executed in the order they arrive. Each incoming variables is formatted as an object type that carries a command value and a time stamp. The Value is generated in the operator station and carried through the system eventually being interpreted by the microcontroller. The Time stamp represents the moment at which the signal was generated in the operator stations and is used for posterior statistical analysis.
  - **Index to Main Program, line 2:** The same variables that are sent to the index node are then relayed to the main program in the control logic node.
  - **Main Program to Microcontroller, line 3:** The information present in this data stream is sent to the microcontroller through a serial communications link at the highest baud rate commonly used for these microcontrollers.
  - **Microcontroller to Cart, line 4:** The control signals sent to the vehicle are formatted as a PWM that is interpreted by the vehicles controller as a RMS voltage that ranges from 0 to 5 volts. The microcontroller also governs a drive for the stepper motor that directs the vehicle’s steering wheel, by sending it the number of steps required for the motor to be in the correct spot.
  - **Cart to Microcontroller, line 5:** Part of the information that is relayed back to the user is captured in the vehicle and sent to the micro controller for processing so that it can be formatted correctly. In this stream, information is sent back as a pulse or data stream depending on the sensor data being acquired.
  - **Microcontroller to Main Program, line 6:** The information is sent back to the main program in the same manner that it was delivered originally to the

microcontroller so that it can either be formatted for sending to the operator page as feedback or for local data acquisition.

- **Cart to Main Program, line 7:** Signals not sent to the microcontroller are sent directly to the main program. These are sent as serial communication streams.
- **Main Program to Index, line 8:** Specific vehicle feedback acquired and formatted in the main program is sent to the Index page**.**

  The feedback signals that are used for augmenting the video streams are parsed, formatted and sent to the index page as internal memory data streams at a periodic rate so as to not saturate communication.
- **Cart to Index, line 9:** The video feedback captured on the cart is sent directly to the index page.
- **Outgoing, line 10:** All of the vehicle feedback and camera streams are lumped together and sent back to the operator page in the same fashion that they are received. In other words, data that is used for the GUI is formatted as an object type that carries a value (no time stamp this time) and sent back asynchronously, while video feedback is simultaneously streamed to the user.

- **Remote Vehicle Control / Nodes:**
  - **Node JS**: The node JS Server is the initial step towards starting the whole system. This server contains the main program that handles the relaying of information to and from the operator (specified in the Index file) and the main program, which computes proper formatting for the control signals and monitors variables that insure system safety.
  - **Index:** This node is programed in HTML and JavaScript. Its main goal is to establish a connection with Opentok, using webRTC, to stream video

feedback and exchange data between the client (operator station) and server (on the remote vehicle). It is the main gateway for incoming and outgoing information and distributes the data accordingly by relaying all control signals to the main program and consolidating video and data feedback for the operator station.

- **Main program**: The main program receives control information from the index module, processes it and relays it back to the vehicle. Specifically, this program scales the information into ranges that the microcontroller can handle, while also monitoring key parameters, such as connectivity and proximity sensors, with the intent of taking emergency actions in case any value passes a predefined safety threshold.

  Simultaneously, it captures feedback of vehicle statistics, like current velocity or direction heading and compiles this into a format that can be transmitted back to the operator station.
- **Microcontroller:** The microcontroller's main function is to relay information to the vehicle in a way that the automobile can interpret the signals and produce an action. In other words, it interprets the serial communication stream coming from the main program and converts the information into a PWM signal that is interpreted as a DC volt signal ranging from 0 to 5 volts in the vehicle controller. It also controls a stepper motor driver by sending the amount of steps that the motor should move in order to reach its required position.

  At the same time, it registers incoming information from several different sensors placed on the vehicle and relays this back to the main program so that it may be formatted and sent back to the operator station.

- **Cart:** Finally the cart is the system which will be controlled. All signals sent through the microcontroller are sensed by the vehicles controller that commands an AC electric motor. On top of this, a stepper motor and drive govern the steering wheel. All these equipment are calibrated so as to allow the lowest possible delay between a received pulse and the execution of an action.

  In addition to controlling the vehicle, sensors are placed in strategic locations that allow for the driver to receive additional information about situations that may not be easily extracted by just looking at the visual feedback provided. These sensors are a GPS device, a 2D LIDAR that scans the mediate proximity in front and a Hall Effect speed sensor that calculates the current velocity. As explained, some sensors are routed to the microcontroller while other go directly to the main program.

Table A-1 List of Remote Vehicle Variables

Variable	**Description**	**L1**	**L2**	**L3**	**L4**	**L5**	**L6**	**L7**	**L8**	**L9**	**L10**
Steering	Steering wheel angle signal from operator: value range from -1 to +1.	X	X								
Steering	Steering wheel angle signal from main program: value range from -450 to +450.			X	X						
Steering Feedback	Steering wheel feedback from encoder: Values range from -7000 to +7000.					X	X				
Acceleration	Acceleration signal from operator: Values range from -1 to +1.	X	X								

Table A-1 Continued

Variable	Description	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10
Acceleration	Acceleration signal from main program: value range from -250 to +250.			X	X						
Brake	Brake signal from operator: Values range from -1 to +1.	X	X								
Brake	Brake signal from main program: value range from -250 to +250.			X	X						
Ignition / Direction	Ignition / Direction signal from operator: Values range from -1 to +1.	X	X								
Ignition / Direction	Ignition / Direction signal from main program: value range from -250 to +250.			X	X						
LIDAR	LIDAR feedback: values are distance and angle and range from 0 to 6 [m] and 270 to 90 degrees.					X	X		X		X
Hall Effect	Pulse detection – wheel counter: values are logical 0 or 1					X	X				
Hall Effect	Distance and Velocity calculation: values are larger than 0.								X		X
GPS	GPS coordinates							X	X		X
Gyroscope	Z-axis of gyroscope reading.							X	X		
Camera Stream	Data stream from cameras									X	X

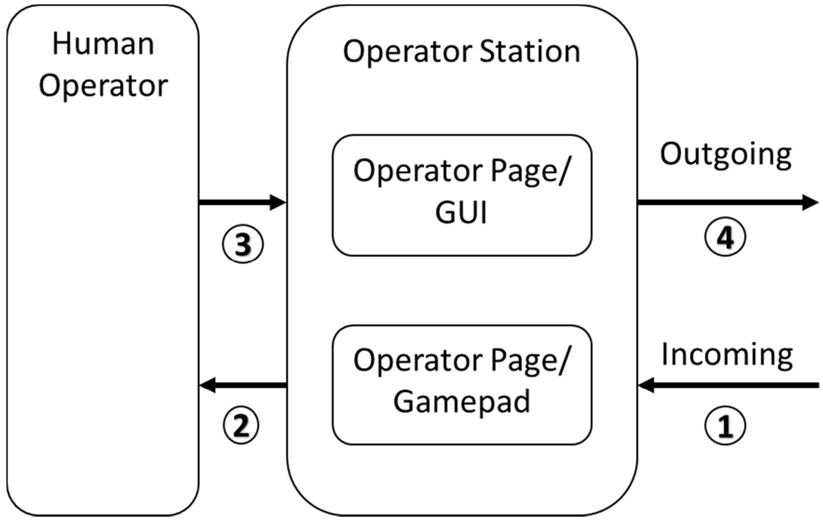

Figure A-2 Local Operator Station Control Nodes and Information Flow

Using Figure A-2, a description of the principle flows and nodes is detailed.

- **Operator Station information Flow:**
  - **Incoming:** The incoming information is mainly composed of the video stream session held by webRTC, and supplementary info such as GPS position or LIDAR point cloud.
  - **Outgoing:** The outgoing data stream on the Operator side is the same as the incoming stream on the remote side and is detailed in the previous section, as is analogously explained the incoming stream.
- **Operator Station Nodes**
  - **Operator station:** This main node, which contains the two processing programs, is manually started by the driver by accessing the Operator web page through a web browser. Once started, it connects to the remote server and immediately starts poling the gamepad for control signals while requesting permission to receive incoming video streams and supplementary data.

- **Gamepad Node:** This node represents the direct interaction that the driver has with the operator station with the intent of controlling the remote vehicle. Here, the user must physically manipulate the different elements, i.e. steering wheel, gas pedals, etc. which are logged and compiled into data packets that are sent as quickly as possible to the remote server. Ideally one would like to poll the input devices as fast as possible, unfortunately high data acquisition frequencies may saturate the communications link, thus a balance must be found between provide sufficient polling for smooth control while not posing a significant threat to the stability of the communications link.
- **Graphics display node:** As the main operator page is initialized, three windows are opened and available to the operator to be resized and fit to each screen so as to provide him with the most comfortable setup allowable. Each window is labeled with the camera view that it will display and has a button that, when toggled, enables the particular video stream commence in said window. Furthermore, the front view window also incorporates in it the rear view in the bottom right side, allowing for more information to be shown more densely.

Table A-2 Equipment Description

Equipment Name	**Make/Model**
Laptop	Lenovo ThinkPad, intel I5, 2x2.53 GHz, 4 GB RAM, 64-bit windows 7.
4G LTE Modem	AT&T Modem; Netgear Aircard 770S.

Table A-2 Continued

Equipment Name	Make/Model
Microcontroller	Arduino Mega 2560 (ATmega2560)
Vehicle Controller	ACD4805-G5 Controller for EZGO RXV
LIDAR	Robo Peak RPLidar 360
Hall Effect Sensor	Hall Effect Sensor - US1881
Gyroscope	ITG-3200 - triple-axis digital-output gyroscope
Stepper Motor	Kolmorgen P70530 step motor and drive.
Video Camera	Panasonic Action Camera HX-A1MD
Operator Station CPU	Intel core I7, 2x2.8 GHz, 6 GB RAM, 64-bit windows 7.
Game Pad	Logitech Racing Wheel G27

APPENDIX B

QUESTIONAIRE AND RESULTS

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

For the following questions, please rate on a scale of 1 to 6. In some cases, you will be asked to choose between one option and the other, and a binary scale will be shown.

REGARDING FEEDBACK

Visual feedback:

1) Did you experience video quality problem? Understand problems as reduced resolution or low frame rate.

1	2	3	4	5	6

1- A lot of Problems 6- No problems

2) Of the issues related to video quality, how good was the resolution?

1	2	3	4	5	6

1- very bad 6- very good

3) Of the issues related to video quality, how good was the frame rate?

1	2	3	4	5	6

1- very bad 6- very good

4) How did the video quality affect your performance?

1	2	3	4	5	6

1-barely affected 6-heavily affected

5) Which parameter, if improved, would most affect your performance?

1	2

1- resolution 2- frames per second

Camera display and swivel camera:

6) I found that the Graphics User Interface was…

1	2	3	4	5	6

1-Counter intuitive 6-Intuitive

7) I felt that changing between camera views or toggling them on and off was…

1	2	3	4	5	6

1-Difficult 6-Simple

8) When turning a camera stream on or off, I felt…

1	2	3	4	5	6

1- It took too long 6-It was Quick

9) I felt that using the swivel cam was…

1	2	3	4	5	6

1-Difficult 6-Simple

10) The time it took to switch viewing angles with the swivel cam was…

1	2	3	4	5	6

1-Too long 6-Quick

11) Comparing more camera views directly to one camera that swivels, I prefer…

1	2	3	4	5	6

1- Only swivel cam 6- More camera views

12) Having the choice between more cameras and lower quality or less cameras and higher quality I prefer…

1	2	3	4	5	6

1-less cameras 6-More cameras

13) Taking into account video quality, I believe my performance would be enhanced with…

1	2	3	4	5	6

1- Only swivel cam 6- More camera views

14) Hypothetically, if there were no limitations on the amount of cameras that could correctly stream video and taking into account the time it takes to turn on or switch camera views, I prefer

1	2	3	4	5	6

1- Only swivel cam 6- More camera views

15) The rear camera setup was…

1	2	3	4	5	6

1-Counter intuitive 6- Intuitive

Regarding Camera positioning:

16) I preferred driving the vehicle with the cameras positioned…

1	2

1- Outside 2- Inside

17) With the camera positioned outside, my spatial awareness was…

1	2	3	4	5	6

1- Poor 6- Excellent

18) With the camera positioned inside, my spatial awareness was…

1	2	3	4	5	6

1- Poor 6- Excellent

Regarding Additional Feedback Sensors:

19) If Audio feedback was present, how do you believe it would affect your performance?

1	2	3	4	5	6

1- Hinder 6- Improve

20) If Force feedback was present, how do you believe it would affect your performance?

1	2	3	4	5	6

1- Hinder 6- Improve

REGARDING AUXILARY FEEDBACK

Regarding the Prediction line (green and red lines on the front camera view)

21) Was the prediction line useful?

1	2	3	4	5	6

1- Not Helpful 6-Very helpful

22) The prediction line was useful in establishing where the vehicle would be in the near future.

1	2	3	4	5	6

1- Disagree 6- Agree completely

23) The prediction line was useful because I had visual feedback as to the inputs that I was sending to the cart.

1	2	3	4	5	6

1- Disagree 6- Agree completely

24) If the prediction line was not present my performance would…

1	2	3	4	5	6

1- Diminish 6- Improve

REGARDING TIME DELAY IN CONTROLS

Regarding time delay

25) How much time delay in controls did you experience?

1	2	3	4	5	6

1- Insignificant 6- Significant

26) Independent of whether the time delay in controls was significant or not, rate the variation of the time delay, i.e. a high variability in the time delay implies that time delay varied several times from high lag to low lag.

1	2	3	4	5	6

1- Very variable 6- Very stable

27) Not considering visual quality issues, the time delay I was exposed to affected my performance...

1	2	3	4	5	6

1- Significantly 6- Very little

REGARDING THEOVERALL SYSTEM

28) My performance was

1	2	3	4	5	6

1- Inadequate 6- Adequate

29) If the time delay in the controls was reduced, my performance would…

1	2	3	4	5	6

1- Be hindered 6- Improve significantly

30) If the resolution of the video was improved, my performance would…

1	2	3	4	5	6

1- Be hindered 6- Improve significantly

31) If the frame rate was increased, my performance would…

1	2	3	4	5	6

1- Be hindered 6- Improve significantly

32) If I had more camera views on continually, my performance would…

1	2	3	4	5	6

1- Be hindered — 6- Improve significantly

33) To what extent did the User Interface affect my performance

1	2	3	4	5	6

1- Slightly — 6- Significantly

34) What most hindered my performance was…

____

35) Please add any additional comments that you believe are pertinent to this survey and were not fully addressed.

____

The Results to the questionnaire are detailed herein as a frequency distribution.

NASA TLX Results:

Scale	1	2	3	4	5	6	7	8	9	10
Q1	0.00	0.00	0.00	0.05	0.00	0.10	0.05	0.00	0.05	0.00
Q2	0.30	0.05	0.10	0.05	0.05	0.00	0.05	0.00	0.05	0.05
Q3	0.15	0.05	0.05	0.00	0.05	0.10	0.05	0.00	0.05	0.05
Q4	0.00	0.00	0.05	0.00	0.05	0.10	0.10	0.05	0.10	0.10
Q5	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.10	0.05	0.10
Q6	0.00	0.05	0.05	0.05	0.05	0.05	0.10	0.05	0.00	0.00

Scale	11	12	13	14	15	16	17	18	19	20
Q1	0.20	0.00	0.05	0.05	0.15	0.05	0.25	0.00	0.00	0.00
Q2	0.20	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Q3	0.15	0.10	0.05	0.15	0.00	0.00	0.00	0.00	0.00	0.00
Q4	0.05	0.10	0.10	0.05	0.00	0.15	0.00	0.00	0.00	0.00
Q5	0.15	0.00	0.05	0.05	0.05	0.15	0.10	0.10	0.05	0.00
Q6	0.15	0.05	0.05	0.05	0.10	0.20	0.00	0.00	0.00	0.00

Questionnaire Results:

Scale	1	2	3	4	5	6
Q1	0.00	0.00	0.00	0.05	0.00	0.95
Q2	0.30	0.05	0.10	0.05	0.05	0.45
Q3	0.15	0.05	0.05	0.00	0.05	0.70
Q4	0.00	0.00	0.05	0.00	0.05	0.90
Q5	0.00	0.00	0.00	0.05	0.00	0.95
Q6	0.00	0.05	0.05	0.05	0.05	0.80
Q7	0.10	0.30	0.15	0.10	0.05	0.30
Q8	0.05	0.10	0.40	0.15	0.15	0.15
Q9	0.15	0.15	0.20	0.25	0.15	0.10
Q10	0.10	0.05	0.20	0.10	0.40	0.15
Q11	0.20	0.80	0.00	0.00	0.00	0.00
Q12	0.00	0.00	0.00	0.25	0.40	0.35
Q13	0.00	0.00	0.05	0.10	0.20	0.65
Q14	0.05	0.05	0.10	0.35	0.25	0.20
Q15	0.00	0.00	0.05	0.05	0.15	0.75
Q16	0.00	0.05	0.00	0.05	0.40	0.50
Q17	0.10	0.20	0.20	0.15	0.05	0.30
Q18	0.20	0.40	0.05	0.20	0.15	0.00
Q19	0.10	0.30	0.20	0.25	0.10	0.05
Q20	0.00	0.10	0.10	0.15	0.30	0.35
Q21	0.05	0.05	0.05	0.20	0.35	0.30
Q22	0.20	0.80	0.00	0.00	0.00	0.00
Q23	0.15	0.20	0.10	0.25	0.25	0.05
Q24	0.00	0.05	0.05	0.30	0.35	0.25
Q25	0.00	0.00	0.00	0.45	0.25	0.30
Q26	0.00	0.00	0.15	0.10	0.40	0.35
Q27	0.00	0.00	0.10	0.05	0.45	0.40
Q28	0.00	0.00	0.10	0.20	0.30	0.40
Q29	0.00	0.00	0.00	0.20	0.40	0.40
Q30	0.30	0.45	0.25	0.00	0.00	0.00
Q31	0.10	0.30	0.10	0.15	0.20	0.15
Q32	0.15	0.15	0.15	0.15	0.30	0.10
Q33	0.05	0.25	0.10	0.30	0.20	0.10

APPENDIX C

RESULTS – PERFORMANCE METRICS

This Appendix details the calculated values of the performance metrics for every task executed by the subjects. Each row in the main table represents a different subject and the columns represent the performance metric value to the corresponding task. Table C-1 correlates the column identification label with the actual performance metric.

Table C - 1 Correlation between Column and Performance metric

Column	**Performance Metric**
Area	Area [m^2]
Length	Length of Run [m]
A/L	Ratio of Area over Length [-]
Max. D.	Maximum Distance Deviation [m]
Str. Cor.	Steering Correction [-]
Acc. Cor.	Acceleration Correction [-]
Brk. Cor.	Brake Correction [-]
Max. Sp.	Maximum Speed [m/s]
Av. Sp.	Average Speed [m/s]
A/T	Area in Function of Time [-]
Av. M. Sp.	Average Moving speed [m/s]
SD. M. Sp.	Standard Deviation of Moving Speed [m/s]
Stops	Stops [-]
T. Mov.	Time Moving [s]
T. Stp.	Time Stopped [s]
T. Run	Time of Run [s]
T. Ini.	Time to Initialize [s]
T.S/T.M.	Ratio of Time Stopped over Moving Time [-]
T.S./T.T.	Ratio of Time of Stopped over Total Time [-]

Table C-1 Continued

T.M./T.T.	Ratio of Time Moving over Total Time [-]
T. of D.	Time of Day [h]
Av. Lag	Mean Latency [ms]
S.D. Lag	Standard Deviation of Latency [ms]

Table C - 2 Path Following Camera Inside

Area	Length	A/L	Max. D.	Str. Cor.	Acc. Cor	Brk. Cor.	Max. Sp	Av. Sp.	A/T	Av. M. Sp.
64.24269	87.89728	0.730884	4.888466	31	25	9	2.743363	0.312823	6372.5	1.2297
45.66588	89.0305	0.512924	3.233932	34	35	8	1.911	0.308108	4573.015	1.2680
108.6114	87.21418	1.245341	5.087353	19	17	5	2.318795	0.445353	5737.143	1.2129
68.83962	92.39096	0.74509	3.98712	23	29	6	2.404676	0.561111	2337.613	1.0727
38.35807	93.79436	0.408959	1.794281	35	21	4	2.434734	0.730384	883.2384	1.2751
116.7575	117.3416	0.995022	4.43547	31	55	22	1.95452	0.410095	7618.581	1.0138
57.87079	94.81366	0.610363	3.93243	41	39	11	2.318795	0.468431	2719.757	1.0585
100.3666	115.2478	0.870877	2.649327	66	43	13	1.636796	0.233826	10885.83	0.7294
72.5172	94.3103	0.768921	3.557982	44	36	14	1.583567	0.223525	5849.01	0.7460
141.5441	97.5162	1.451493	5.163758	18	21	6	2.016038	0.583666	3855.086	1.2317
76.15319	88.2038	0.863378	4.066671	14	10	5	2.008028	0.736712	2353.94	1.1896
73.29974	95.38715	0.768445	3.064837	22	35	11	2.213395	0.599549	3036.747	1.2514
58.17601	86.05521	0.676031	4.827348	30	31	3	1.803507	0.562838	2676.755	1.1297
158.7171	107.6479	1.474409	6.861242	28	21	6	2.008028	0.53218	5779.07	1.0977
100.594	100.0323	1.005615	4.095107	22	21	7	1.946	0.762236	2995.28	1.3447
150.0286	96.74272	1.5508	9.828469	34	29	7	1.872873	0.577233	4926.804	1.0710
101.224	100.2605	1.00961	4.223937	30	52	15	2.072114	0.388724	8195.909	0.9653
129.4814	93.84011	1.379808	4.880369	22	21	7	2.188525	0.582049	5964.13	1.0831
114.1539	93.05264	1.226767	5.047022	42	39	5	2.11716	0.563614	5665.708	1.0819
120.0226	105.4863	1.137803	8.170613	62	71	36	1.75553	0.290591	7402.716	0.9607

Table C – 2 Continued

SD. M.Sp.	Stops	T. Mov.	T. Stp.	T. Run	T. Ini.	T.S./T.M.	T.S./T.T.	T.M./T.T.	T. of D.	Av. Lag	S.D. Lag
0.4860	4	101.58	179.24	280.81	265.80	1.765	0.638	0.362	20.583	561.645	667.223
0.5686	8	102.55	186.35	288.91	80.67	1.817	0.645	0.355	18.983	1421.468	1759.177
0.4750	5	92.80	102.70	195.50	43.09	1.107	0.525	0.475	19.850	274.249	273.897
0.5025	4	130.63	33.91	164.54	191.03	0.260	0.206	0.794	16.067	647.287	546.877
0.4757	4	87.70	40.57	128.27	31.99	0.463	0.316	0.684	16.950	77.918	41.543
0.4932	12	163.37	122.55	285.93	21.85	0.750	0.429	0.571	17.200	2031.308	2371.076
0.5047	8	122.70	79.39	202.08	91.31	0.647	0.393	0.607	18.400	484.535	617.045
0.3677	11	215.30	277.00	492.31	55.89	1.287	0.563	0.437	19.033	116.714	799.627
0.4290	13	190.83	230.93	421.76	66.33	1.210	0.548	0.452	20.067	102.593	25.187
0.4634	5	100.45	66.41	166.86	62.77	0.661	0.398	0.602	19.133	98.428	70.814
0.4539	3	92.58	26.93	119.50	31.87	0.291	0.225	0.775	19.700	83.357	41.703
0.5229	7	102.93	55.94	158.86	35.88	0.543	0.352	0.648	19.167	111.127	113.575
0.4351	5	92.99	59.97	152.96	22.33	0.645	0.392	0.608	19.633	119.418	117.838
0.3754	4	119.82	82.21	202.03	83.58	0.686	0.407	0.593	17.867	749.084	1028.128
0.5174	5	86.98	44.11	131.09	34.98	0.507	0.336	0.664	20.617	194.292	256.477
0.4416	9	112.82	54.54	167.37	20.12	0.483	0.326	0.674	15.450	688.998	1454.423
0.4892	12	144.38	113.67	258.05	22.73	0.787	0.440	0.560	19.700	405.460	664.224
0.4505	8	111.28	50.02	161.30	65.11	0.450	0.310	0.690	19.100	94.561	49.834
0.4939	8	112.88	51.97	164.85	25.17	0.460	0.315	0.685	18.917	697.153	1072.517
0.4792	14	161.28	201.35	362.62	70.87	1.248	0.555	0.445	16.033	636.138	640.590

Table C - 3 Path Following Camera Outside

Area	Length	A/L	Max. D.	Str. Cor.	Acc. Cor	Brk. Cor.	Max. Sp	Av. Sp.	A/T	Av. M. Sp.
68.45724	87.77871	0.779884	3.42637	35	49	11	1.498298	0.174432	9869.227	0.816942
68.45724	87.77871	0.779884	3.42637	35	49	11	1.498298	0.174432	9869.227	0.816942
70.99353	83.42185	0.851018	3.570715	14	25	3	2.188525	0.374159	6751.261	1.044348
60.4654	93.61937	0.645864	4.465372	31	30	15	1.882234	0.474995	3690.491	1.101347
42.09235	91.61888	0.459429	1.529097	36	27	6	2.188525	0.556318	1429.141	1.199922
151.5726	109.7326	1.381291	5.160174	37	45	23	2.021583	0.413227	10133.65	1.297457
49.95465	87.41656	0.571455	2.518123	39	41	10	2.375351	0.448195	2732.5	0.942824
103.4208	106.6938	0.969323	5.047023	42	43	13	1.803507	0.289198	12301.09	0.985687
67.62875	87.00289	0.777316	3.453852	53	52	30	1.837535	0.253258	10657.52	0.88841
107.8661	96.76128	1.114765	4.106113	31	21	1	2.072114	0.359783	5912.987	1.021842
73.05215	83.05803	0.879531	2.471936	25	17	8	2.164208	0.620616	1761.434	1.223552
56.43072	87.31979	0.646254	2.674804	44	35	12	2.264869	0.422452	2367.802	1.13179
45.66943	78.40899	0.582451	2.556567	24	23	3	1.909596	0.488608	1945.259	1.190567
81.39098	101.1931	0.804313	4.895231	38	41	7	2.015	0.328305	8252.434	0.992921
73.56432	87.03871	0.845191	3.651997	27	17	6	2.188525	0.652873	2816.252	1.304662
216.424	123.6354	1.750503	7.373601	42	45	5	1.969	0.406444	11388.32	1.039356
43.45946	92.06667	0.472043	1.659728	20	33	3	1.872873	0.494719	2325.875	0.994877
219.897	105.1172	2.091923	14.25785	27	29	14	2.050303	0.594864	10364.05	1.177853
180.2926	120.6917	1.493828	9.205496	51	63	23	1.773	0.458369	10103.75	1.189642
138.3527	112.1302	1.233858	5.931503	62	65	37	2.188525	0.259612	18936.27	0.863392

Table C - 3 Continued

SD. M.Sp.	Stops	T. Mov.	T. Stp.	T. Run	T. Ini.	T.S./T.M.	T.S./T.T.	T.M./T.T.	T. of D.	Av. Lag	S.D. Lag
0.396063	9	162.119	340.372	502.491	34.265	2.09952	0.67737	0.32263	19.750	175.147	364.176
0.396063	9	162.119	340.372	502.491	34.265	2.09952	0.67737	0.32263	17.750	175.147	364.176
0.464036	7	111.631	111.176	222.807	43.87	0.99592	0.49898	0.50102	19.250	117.423	92.934
0.475196	6	117.572	79.259	196.831	20.135	0.67413	0.40268	0.59732	15.600	1051.341	1471.814
0.502625	5	100.459	64.448	164.907	58.297	0.64154	0.39081	0.60919	16.783	98.479	58.014
0.508241	9	104.973	160.874	265.847	49.389	1.53253	0.60514	0.39486	16.917	2113.302	2023.450
0.457685	9	121.268	73.426	194.694	24.366	0.60549	0.37714	0.62286	18.183	186.021	231.124
0.421152	7	135.639	232.773	368.412	48.876	1.71612	0.63183	0.36817	18.617	75.788	74.805
0.459033	10	143.761	200.023	343.784	72.499	1.39136	0.58183	0.41817	19.667	79.879	29.134
0.475939	8	132.627	135.897	268.524	90.494	1.02466	0.50609	0.49391	18.867	168.691	269.360
0.503962	4	94.254	39.445	133.699	44.325	0.41850	0.29503	0.70497	19.533	89.395	47.341
0.501256	9	106.054	100.043	206.097	52.903	0.94332	0.48542	0.51458	18.950	146.837	183.077
0.506775	7	93.841	66.811	160.652	42.84	0.71196	0.41587	0.58413	19.450	136.645	131.884
0.690795	12	148.739	159.176	307.915	48.48	1.07017	0.51695	0.48305	16.983	1378.763	1824.191
0.488319	6	82.662	50.398	133.06	28.708	0.60969	0.37876	0.62124	20.233	416.506	471.858
0.541888	12	173.114	131.195	304.309	75.394	0.75785	0.43112	0.56888	15.200	2098.850	2238.089
0.465829	10	124.777	61.057	185.834	23.093	0.48933	0.32856	0.67144	19.517	467.916	641.928
0.490247	7	123.787	52.7	176.487	37.736	0.42573	0.29861	0.70139	18.883	79.793	34.355
0.790078	10	132.358	130.679	263.037	49.202	0.98731	0.49681	0.50319	18.667	1454.403	2145.347
0.441323	16	180.177	251.227	431.404	33.418	1.39433	0.58235	0.41765	15.850	1359.191	1477.937

Table C - 4 Reverse Trajectory Camera Inside

Area	Length	A/L	Max. D.	Str. Cor.	Acc. Cor	Brk. Cor.	Max. Sp	Av. Sp.	A/T	Av. M. Sp.
41.57257	39.02607	1.065251	5.131931	20	23	8	1.724	0.138	3899.350	0.646
34.09267	39.38154	0.865702	1.711552	11	7	11	1.694	0.355	1958.823	0.869
21.77823	40.74479	0.534504	1.181725	11	7	5	1.443	0.313	1223.812	0.683
71.36786	58.16074	1.22708	4.193533	24	25	7	2.630	0.413	3842.050	0.992
8.556563	39.40585	0.217139	0.828077	12	7	4	1.873	0.708	237.028	1.003
14.85317	38.83397	0.382479	1.077039	18	26	7	2.008	0.355	737.378	0.672
20.10935	40.82914	0.492524	1.328511	16	18	5	1.820	0.354	926.799	0.738
41.22564	38.6811	1.065782	2.05757	16	21	11	0.989	0.195	3408.318	0.537
32.32845	40.05045	0.807193	2.185732	11	21	7	1.353	0.310	2071.289	0.672
20.47729	39.82613	0.514167	1.294146	17	7	7	1.257	0.417	1334.014	0.747
30.99754	41.1906	0.752539	2.503987	14	5	3	1.584	0.498	1156.246	0.797
25.00731	40.46769	0.617957	2.09053	16	21	5	2.140	0.508	1108.326	0.808
19.00355	38.51615	0.493392	1.276861	10	9	3	1.558	0.450	721.429	0.792
29.17572	42.71937	0.682962	2.565041	33	35	5	2.362	0.118	5531.610	0.651
41.12605	41.02753	1.002401	2.369771	12	12	3	2.050	0.637	1315.706	1.062
24.15113	39.62031	0.609564	1.88548	11	13	2	2.008	0.362	1240.467	0.747
12.57602	41.56643	0.302552	0.748812	7	19	3	1.610	0.482	396.521	0.744
16.68347	60.90549	0.273924	0.792468	25	29	16	1.498	0.323	1158.052	0.677
15.18236	39.45102	0.384841	1.05701	35	31	4	1.353	0.353	792.955	0.644
24.18531	42.15122	0.573775	1.705979	53	77	14	1.838	0.136	2678.019	0.516

Table C - 4 Continued

SD. M.Sp.	Stops	T. Mov.	T. Stp.	T. Run	T. Ini.	T.S./T.M.	T.S./T.T.	T.M./T.T.	T. of D.	Av. Lag	S.D. Lag
0.298195	4	71.802	208.639	280.441	69.092	2.906	0.744	0.256	20.317	114.894	46.737
0.357441	4	52.48	57.717	110.197	48.278	1.100	0.524	0.476	18.900	256.399	239.691
0.263432	4	65.344	64.27	129.614	57.122	0.984	0.496	0.504	19.767	68.585	16.754
0.722609	9	90.582	50.057	140.639	18.841	0.553	0.356	0.644	15.983	2439.556	2424.143
0.291757	2	41.755	13.509	55.264	31.923	0.324	0.244	0.756	16.917	108.046	73.433
0.357935	5	68.588	40.093	108.681	24.631	0.585	0.369	0.631	17.083	532.169	587.075
0.359343	7	71.447	42.968	114.415	59.197	0.601	0.376	0.624	18.317	1028.109	1106.917
0.228521	7	79.064	117.313	196.377	41.168	1.484	0.597	0.403	18.933	70.517	23.330
0.307556	5	70.734	57.51	128.244	112.829	0.813	0.448	0.552	19.867	89.316	70.790
0.256591	4	62.039	32.744	94.783	65.732	0.528	0.345	0.655	19.067	106.918	56.990
0.347589	3	62.797	19.34	82.137	39.834	0.308	0.235	0.765	19.650	91.355	46.625
0.366805	7	58.315	20.986	79.301	51.793	0.360	0.265	0.735	19.100	154.769	118.811
0.317606	2	58.228	27.043	85.271	41.063	0.464	0.317	0.683	19.583	141.475	149.874
0.550851	13	94.408	266.317	360.725	27.272	2.821	0.738	0.262	17.733	816.994	1194.974
0.381299	2	46.186	17.717	63.903	61.756	0.384	0.277	0.723	20.550	229.298	279.420
0.339201	3	60.88	47.88	108.76	20.202	0.786	0.440	0.560	15.383	242.814	114.725
0.274096	3	60.981	24.704	85.685	22.423	0.405	0.288	0.712	19.650	579.102	521.133
0.312815	10	107.447	80.064	187.511	69.759	0.745	0.427	0.573	19.017	93.142	39.591
0.247516	7	67.166	43.844	111.01	21.484	0.653	0.395	0.605	18.850	148.279	115.805
0.481703	19	123.672	184.476	308.148	53.75	1.492	0.599	0.401	15.200	1908.960	2214.540

Table C - 5 Reverse Trajectory Camera Outside

Area	Length	A/L	Max. D.	Str. Cor.	Acc. Cor	Brk. Cor.	Max. Sp	Av. Sp.	A/T	Av. M. Sp.
26.869	36.699	0.732	1.824	15	41	8	0.932	0.174	3939.067	0.419
19.387	37.459	0.518	1.018	11	9	3	1.584	0.254	1276.911	0.744
43.773	55.353	0.791	3.457	17	15	16	2.029	0.275	5145.723	0.773
15.106	39.205	0.385	1.172	20	28	11	1.571	0.185	1530.611	0.663
17.322	42.692	0.406	1.655	18	7	11	1.709	0.583	564.388	0.855
6.671	38.526	0.173	0.562	22	22	7	1.584	0.416	579.160	0.861
14.890	39.337	0.379	2.201	28	41	7	1.009	0.281	1099.984	0.542
60.103	39.878	1.507	2.716	10	17	5	1.059	0.282	4479.383	0.598
34.665	38.009	0.912	2.913	41	59	12	0.812	0.134	2692.710	0.373
25.763	40.647	0.634	1.762	16	21	5	1.325	0.305	1489.571	0.602
17.293	37.457	0.462	1.308	10	3	3	1.584	0.455	504.882	0.801
27.974	46.080	0.607	1.672	15	30	15	2.164	0.361	1190.374	0.885
8.233	38.436	0.214	0.701	14	11	5	1.891	0.436	420.811	0.828
40.041	52.891	0.757	3.044	28	25	5	2.050	0.275	4145.696	0.723
43.480	38.644	1.125	2.040	17	18	3	1.534	0.335	2152.304	0.786
15.150	37.656	0.402	2.236	9	9	3	1.510	0.397	1262.617	0.728
16.838	39.543	0.426	1.038	10	15	3	1.225	0.372	957.410	0.641
14.704	42.215	0.348	0.967	20	25	4	1.454	0.311	1154.106	0.687
17.913	39.101	0.458	1.020	20	31	5	1.353	0.294	1534.863	0.596
67.214	66.321	1.013	4.850	38	50	43	1.761	0.209	7114.516	0.763

Table C - 5 Continued

SD. M.Sp.	Stops	T. Mov.	T. Stp.	T. Run	T. Ini.	T.S./T.M.	T.S./T.T.	T.M./T.T.	T. of D.	Av. Lag	S.D. Lag
0.2055	8	98.683	110.346	209.029	27.24	1.1182	0.5279	0.4721	19.65	124.4194	271.7045
0.3155	3	62.008	84.366	146.374	24.674	1.3606	0.5764	0.4236	17.98	330.3040	431.5126
0.4363	6	100.109	100.493	200.602	66.208	1.0038	0.5010	0.4990	19.15	466.6873	734.7643
0.2997	7	67.144	143.323	210.467	31.028	2.1346	0.6810	0.3190	15.48	716.2281	896.8088
0.3219	2	57.792	14.987	72.779	79.582	0.2593	0.2059	0.7941	16.72	578.2803	716.7904
0.3943	4	59.609	32.674	92.283	18.182	0.5481	0.3541	0.6459	16.85	75.4875	29.6278
0.2317	9	79.78	59.69	139.47	48.829	0.7482	0.4280	0.5720	18.12	807.7530	858.6846
0.2424	4	79.438	60.918	140.356	57.837	0.7669	0.4340	0.5660	18.55	70.3410	36.0162
0.2118	11	121.407	160.199	281.606	72.425	1.3195	0.5689	0.4311	19.55	66.5191	29.4766
0.3271	8	83.52	48.742	132.262	78.394	0.5836	0.3685	0.6315	18.78	179.5048	180.4405
0.3358	3	58.118	23.66	81.778	39.811	0.4071	0.2893	0.7107	19.48	94.0154	48.8507
0.4211	9	59.209	68.294	127.503	69.4	1.1534	0.5356	0.4644	18.88	401.6120	607.4483
0.3677	3	56.106	31.503	87.609	32.088	0.5615	0.3596	0.6404	19.38	145.8415	150.4573
0.3894	11	90.018	101.882	191.9	64.242	1.1318	0.5309	0.4691	16.88	1316.1312	1696.3897
0.3361	4	58.745	55.945	114.69	54.179	0.9523	0.4878	0.5122	20.17	513.4148	591.0102
0.2478	4	56.509	37.784	94.293	28.843	0.6686	0.4007	0.5993	14.23	764.3874	833.8427
0.2185	6	64.219	41.426	105.645	21.735	0.6451	0.3921	0.6079	19.45	249.8973	333.0546
0.3696	7	76.46	58.407	134.867	61.018	0.7639	0.4331	0.5669	18.80	350.5963	611.3708
0.2937	10	73.975	59.218	133.193	46.234	0.8005	0.4446	0.5554	18.58	350.1714	399.2239
0.4785	11	131.706	184.059	315.765	78.638	1.3975	0.5829	0.4171	15.70	2380.7132	2826.0838

Table C - 6 Straight Trajectory Camera Inside

Area	Length	A/L	Max. D.	Str. Cor.	Acc. Cor	Brk. Cor.	Max. Sp	Av. Sp.	A/T	Av. M. Sp.
10.562	34.955	0.302	0.479	10	3	0	2.117	1.363	165.451	1.544
17.452	33.183	0.526	0.893	5	1	2	2.008	1.318	250.908	1.474
2.604	35.964	0.072	0.212	2	3	1	1.584	1.039	46.879	1.164
7.674	35.096	0.219	0.781	6	9	1	1.755	1.357	150.164	1.431
5.829	34.292	0.170	0.464	13	1	1	2.189	1.563	100.197	1.629
16.643	34.504	0.482	0.928	9	11	1	2.563	0.761	387.773	1.279
7.416	34.750	0.213	0.301	8	3	1	2.239	1.459	94.232	1.549
14.565	35.945	0.405	0.937	9	9	7	1.487	0.512	480.167	0.885
14.981	35.104	0.427	0.846	12	9	2	1.498	0.726	453.963	0.880
23.525	36.543	0.644	1.271	4	1	1	1.724	1.185	394.522	1.291
13.064	35.761	0.365	0.582	4	1	2	1.838	1.409	171.467	1.505
5.078	34.349	0.148	0.561	5	3	1	2.668	1.466	91.387	1.578
10.801	35.179	0.307	0.523	9	3	2	1.771	1.372	162.760	1.419
7.916	36.908	0.214	0.643	6	9	2	2.375	1.038	153.994	1.232
5.603	35.546	0.158	0.355	5	1	2	3.142	1.403	75.206	1.476
25.390	34.530	0.735	1.023	6	7	1	1.771	1.294	364.067	1.459
10.122	35.487	0.285	0.483	3	3	2	2.951	1.299	137.113	1.426
22.471	37.141	0.605	0.938	8	1	1	1.929	1.349	300.278	1.476
12.841	35.155	0.365	0.860	21	7	2	1.820	1.151	259.959	1.209
6.471	34.004	0.190	0.506	6	11	4	1.787	0.852	138.917	0.955

Table C - 6 Continued

SD. M.Sp.	Stops	T. Mov.	T. Stp.	T. Run	T. Ini.	T.S./T.M.	T.S./T.T.	T.M./T.T.	T. of D.	Av. Lag	S.D. Lag
0.284	2	23.6	2.0	25.6	107.4	0.1	0.1	0.9	20.0	121.7	48.3
0.292	1	25.1	0.0	25.1	36.8	0.0	0.0	1.0	18.9	115.2	39.2
0.305	1	34.7	0.0	34.7	69.8	0.0	0.0	1.0	19.7	60.5	16.7
0.255	1	25.0	0.0	25.0	31.6	0.0	0.0	1.0	15.5	57.3	13.3
0.255	1	21.9	0.0	21.9	74.7	0.0	0.0	1.0	16.9	73.2	51.5
0.417	2	30.4	14.9	45.3	20.2	0.5	0.3	0.7	17.2	291.1	276.8
0.289	1	23.8	0.0	23.8	66.9	0.0	0.0	1.0	18.3	91.1	63.2
0.348	3	53.4	16.6	69.9	72.0	0.3	0.2	0.8	18.8	52.2	33.7
0.287	2	46.0	2.4	48.3	77.4	0.1	0.0	1.0	19.8	73.7	46.3
0.293	1	30.7	0.0	30.7	115.0	0.0	0.0	1.0	19.0	108.7	130.9
0.251	1	25.3	0.0	25.3	40.9	0.0	0.0	1.0	19.6	98.7	103.0
0.290	1	23.4	0.0	23.4	76.8	0.0	0.0	1.0	19.1	88.8	76.8
0.232	1	25.7	0.0	25.7	26.8	0.0	0.0	1.0	19.6	62.8	24.3
0.356	1	35.5	0.0	35.5	42.3	0.0	0.0	1.0	17.7	150.1	149.3
0.260	1	25.3	0.0	25.3	34.0	0.0	0.0	1.0	20.5	68.7	17.3
1.264	1	26.6	0.0	26.6	29.2	0.0	0.0	1.0	15.3	632.2	566.9
0.301	1	27.3	0.0	27.3	22.8	0.0	0.0	1.0	19.6	90.3	54.6
0.275	1	27.4	0.0	27.4	75.9	0.0	0.0	1.0	19.0	86.6	64.3
0.247	1	30.5	0.0	30.5	55.1	0.0	0.0	1.0	18.8	125.9	114.5
0.310	1	40.0	0.0	40.0	44.4	0.0	0.0	1.0	15.2	85.1	63.1

Table C - 7 Straight Trajectory Camera Outside

Area	Length	A/L	Max. D.	Str. Cor.	Acc. Cor	Brk. Cor.	Max. Sp	Av. Sp.	A/T	Av. M. Sp.
78.450	44.800	1.751	7.391	9	7	3	1.8375	0.7124	2827.9729	1.2586
4.974	33.940	0.147	0.705	4	1	1	1.8204	1.3206	128.6993	1.4172
3.011	35.399	0.085	0.339	3	17	3	1.5836	0.6079	88.6422	1.0850
14.493	35.096	0.413	0.603	6	9	1	1.7548	1.3572	204.5286	1.4305
7.498	34.911	0.215	0.697	11	1	2	2.4047	1.6190	119.5781	1.7079
9.529	35.921	0.265	0.698	6	3	1	2.0080	1.5734	157.1150	1.6539
14.299	39.073	0.366	2.589	9	8	3	2.8229	1.3131	372.7158	1.4875
24.805	34.457	0.720	1.090	6	13	3	1.5337	0.5997	935.7476	0.9956
19.422	33.215	0.585	0.867	11	9	1	1.7548	1.0853	369.3549	1.2622
7.233	35.759	0.202	0.806	1	2	1	2.3284	1.2376	143.0942	1.4379
9.265	34.040	0.272	0.980	5	1	1	1.9096	0.8195	164.2946	1.4831
3.098	33.076	0.094	0.254	10	8	3	2.4656	1.4437	56.3346	1.7031
6.600	33.773	0.195	0.345	8	11	2	1.7086	1.3667	102.9803	1.4420
26.710	34.565	0.773	1.184	8	3	2	1.6368	1.0196	475.0846	1.1200
13.704	35.134	0.390	0.496	5	3	1	2.9966	0.8948	274.0523	1.5348
11.664	34.494	0.338	0.570	5	1	2	2.2134	1.4321	161.3960	1.4947
6.071	34.751	0.175	0.289	5	1	2	2.0080	1.3144	91.9362	1.3944
6.605	36.761	0.180	0.514	10	3	1	2.0721	1.3696	109.9626	1.4747
6.993	34.050	0.205	0.364	16	15	1	1.7086	0.7718	175.2564	0.8527
36.699	37.150	0.988	2.043	11	7	3	2.1404	1.3237	613.2183	1.4377

Table C - 7 Continued

SD. M.Sp.	Stops	T. Mov.	T. Stp.	T. Run	T. Ini.	T.S./T.M.	T.S./T.T.	T.M./T.T.	T. of D.	Av. Lag	S.D. Lag
0.4426	2	47.2	15.4	62.6	49.6	0.3	0.2	0.8	20.0	135.6	159.2
0.2568	1	25.7	0.0	25.7	28.8	0.0	0.0	1.0	18.9	72.4	44.3
0.2725	2	36.3	21.7	58.0	41.6	0.6	0.4	0.6	19.7	65.4	18.7
0.2549	1	25.0	0.0	25.0	31.6	0.0	0.0	1.0	15.5	57.3	13.3
0.2650	1	21.5	0.0	21.5	70.6	0.0	0.0	1.0	16.9	168.0	157.8
0.2305	1	22.8	0.0	22.8	22.0	0.0	0.0	1.0	17.2	80.9	15.8
0.3921	1	29.7	0.0	29.7	120.6	0.0	0.0	1.0	18.3	147.7	141.5
0.3454	2	40.9	16.3	57.2	43.0	0.4	0.3	0.7	18.8	64.8	48.3
0.3232	2	28.3	2.2	30.5	67.4	0.1	0.1	0.9	19.8	77.8	77.8
0.4604	1	28.8	0.0	28.8	55.0	0.0	0.0	1.0	19.0	166.5	153.7
0.2997	2	24.2	17.4	41.6	17.4	0.7	0.4	0.6	19.6	158.2	225.8
0.2904	2	20.5	2.4	22.9	75.7	0.1	0.1	0.9	19.1	85.0	125.5
0.2397	1	24.7	0.0	24.7	38.0	0.0	0.0	1.0	19.6	67.0	19.1
0.2823	1	33.8	0.0	33.8	52.7	0.0	0.0	1.0	17.7	184.3	238.5
0.3441	2	24.3	14.9	39.2	22.9	0.6	0.4	0.6	20.5	71.3	23.3
0.2454	1	24.2	0.0	24.2	19.5	0.0	0.0	1.0	15.3	122.9	22.9
0.2633	1	26.4	0.0	26.4	21.5	0.0	0.0	1.0	19.6	75.0	40.9
0.3054	1	26.7	0.0	26.7	45.9	0.0	0.0	1.0	19.0	215.9	213.2
0.2376	1	43.9	0.0	43.9	35.9	0.0	0.0	1.0	18.8	82.9	41.3
0.2889	1	28.0	0.0	28.0	30.9	0.0	0.0	1.0	15.2	142.0	53.3

APPENDIX D

RESULTS – STATISTICAL ANALYSIS

This Appendix details the calculated values of the statistical analysis completed for each task. Each row in the main table represents a different statistical test and the columns represent the performance metric value to the corresponding test. The first row corresponds to the Kolmogorov-Smirnov Goodness of Fit. The second row, is the output of the F-test if the first row accepts the test or a Levene test if the first row rejects the hypothesis. Lastly, the third row is a two-sample T-test, if the KS-test accepts the hypothesis, or a Kruskal-Wallis test if the first rejects the hypothesis.

For each run, all p-values are detailed and the rejection or non-rejections are shown. An H-value of 1 indicates that the test rejects the null hypothesis.

Table D-1 correlates the column identification label with the actual performance metric.

The two main hypothesis tests are shown in this appendix. The main hypothesis “A vehicle can be controlled over a 4G LTE network streaming HD video Feedback” and the secondary hypothesis “the camera positions have a significant effect on performance when teleoperating a vehicle”.

Table D - 1 Correlation between Column and Performance metric

Column	**Performance Metric**
Area	Area
Length	Length of Run

Table D – 1 Continued

Column	Performance Metric
A/L	Ratio of Area over Length
Max. D.	Maximum Distance Deviation
Str. Cor.	Steering Correction
Acc. Cor.	Acceleration Correction
Brk. Cor.	Brake Correction
Max. Sp.	Maximum Speed
Av. Sp.	Average Speed
A/T	Area in Function of Time
Av. M. Sp.	Average Moving speed
SD. M. Sp.	Standard Deviation of Moving Speed
Stops	Stops
T. Mov.	Time Moving
T. Stp.	Time Stopped
T. Run	Time of Run
T. Ini.	Time to Initialize
T.S/T.M.	Ratio of Time Stopped over Moving Time
T.S./T.T.	Ratio of Time of Stopped over Total Time
T.M./T.T.	Ratio of Time Moving over Total Time

Table D - 2 Main Hypothesis Statistical Tests for Straight Trajectory

Straight Trajectory Statistical test H									
Area	Length	A/L	Max. D.	Str.Cor.	Acc. Cor.	Brk. Cor.	Max. Sp.	Av. Sp.	A/T
1	0	0	1	0	1	1	0	1	1
1	1	1	1	0	1	0	0	1	1
1	1	1	1	0	0	1	1	1	1

Straight Trajectory Statistical test H									
Av. M. Sp.	SD. M. Sp.	Stops	T. Mov.	T. Stp	T. Run	T. Ini.	T.S./T.M.	T.S/T.T.	T.M/T.T.
1	1	1	0	1	1	0	1	1	1
0	0	1	1	1	1	1	1	1	1
1	1	0	1	0	1	1	0	0	0

Straight Trajectory Statistical test P									
Area	Length	A/L	Max. D.	Str.Cor.	Acc. Cor.	Brk. Cor.	Max. Sp.	Av. Sp.	A/T
4.40E-02	5.97E-02	9.95E-02	5.65E-04	1.48E-01	6.46E-03	1.52E-02	2.19E-01	2.81E-02	2.11E-03
2.02E-03	3.89E-04	3.55E-03	2.95E-04	3.22E-01	9.69E-04	6.13E-01	1.68E-01	1.71E-02	6.39E-06
1.68E-03	1.44E-02	5.32E-06	1.01E-03	9.36E-01	5.57E-01	2.51E-03	1.63E-07	3.04E-04	3.50E-04

Straight Trajectory Statistical test P									
Av. M. Sp.	SD. M. Sp.	Stops	T. Mov.	T. Stp	T. Run	T. Ini.	T.S./T.M.	T.S/T.T.	T.M/T.T.
3.57E-02	1.84E-03	1.38E-07	9.23E-02	1.11E-06	1.54E-02	3.77E-01	1.44E-06	6.80E-07	6.80E-07
5.03E-02	7.53E-01	8.83E-04	2.26E-05	1.79E-02	1.26E-02	0.00E+00	2.76E-02	1.62E-02	1.62E-02
3.04E-04	6.01E-04	1.84E-01	2.43E-16	1.88E-01	3.04E-04	1.14E-14	1.88E-01	1.88E-01	1.88E-01

Table D - 3 Main Hypothesis Statistical Test for Reverse Trajectory

Reverse Trajectory Statistical test H									
Area	Length	A/L	Max. D.	Str.Cor.	Acc. Cor.	Brk. Cor.	Max. Sp.	Av. Sp.	A/T
0	1	0	0	0	0	1	0	0	1
1	0	1	1	1	1	0	1	1	1
1	1	1	1	1	1	0	0	1	1

Reverse Trajectory Statistical test H									
Av. M. Sp.	SD. M. Sp.	Stops	T. Mov.	T. Stp	T. Run	T. Ini.	T.S./T.M.	T.S/T.T.	T.M/T.T.
0	0	0	0	1	0	0	0	0	0
0	0	1	1	1	1	1	1	1	1
1	0	1	1	1	1	1	1	1	1

Reverse Trajectory Statistical test P									
Area	Length	A/L	Max. D.	Str.Cor.	Acc. Cor.	Brk. Cor.	Max. Sp.	Av. Sp.	A/T
3.86E-01	3.74E-04	5.74E-01	4.81E-01	6.90E-02	4.30E-01	2.04E-02	8.76E-01	8.08E-01	8.19E-03
2.52E-03	7.63E-02	4.14E-03	1.30E-03	4.31E-03	3.00E-04	1.52E-01	4.56E-03	2.82E-02	9.91E-03
7.88E-06	1.15E-02	9.01E-07	1.20E-07	2.94E-02	6.30E-04	9.85E-01	9.21E-01	2.59E-14	7.83E-04

Reverse Trajectory Statistical test P									
Av. M. Sp.	SD. M. Sp.	Stops	T. Mov.	T. Stp	T. Run	T. Ini.	T.S./T.M.	T.S/T.T.	T.M/T.T.
8.98E-01	3.06E-01	1.24E-01	2.24E-01	2.42E-02	6.80E-02	5.35E-01	9.02E-02	7.97E-01	7.97E-01
1.27E-01	1.29E-01	0.00E+00	6.67E-04	1.89E-02	6.70E-06	0.00E+00	2.12E-04	1.46E-02	1.46E-02
1.01E-06	1.58E-01	6.22E-09	9.80E-13	3.04E-04	7.54E-11	7.80E-17	2.75E-08	8.21E-10	8.21E-10

Table D - 4 Main Hypothesis Statistical Tests for Path Following

Path Following Statistical test H									
Area	Length	A/L	Max. D.	Str.Cor.	Acc. Cor.	Brk. Cor.	Max. Sp.	Av. Sp.	A/T
0	0	0	1	0	0	0	0	0	0
1	1	1	0	0	1	1	1	0	1
1	0	1	1	1	1	1	1	1	1

Path Following Statistical test H									
Av. M. Sp.	SD. M. Sp.	Stops	T. Mov.	T. Stp	T. Run	T. Ini.	T.S./T.M.	T.S/T.T.	T.M/T.T.
0	1	0	0	0	0	1	0	0	0
1	0	1	1	1	1	0	1	1	1
1	1	1	1	1	1	1	1	1	1

Path Following Statistical test P									
Area	Length	A/L	Max. D.	Str.Cor.	Acc. Cor.	Brk. Cor.	Max. Sp.	Av. Sp.	A/T
1.07E-01	3.82E-01	2.17E-01	1.77E-02	8.28E-01	8.98E-01	1.48E-01	9.87E-01	8.05E-01	4.33E-01
5.53E-03	5.13E-06	1.22E-02	2.64E-01	5.78E-02	4.16E-03	1.08E-03	9.58E-03	8.02E-02	1.34E-04
4.18E-10	6.42E-01	1.81E-10	1.01E-03	8.57E-03	3.88E-06	2.28E-04	2.96E-12	9.67E-11	5.01E-11

Path Following Statistical test P									
Av. M. Sp.	SD. M. Sp.	Stops	T. Mov.	T. Stp	T. Run	T. Ini.	T.S./T.M.	T.S/T.T.	T.M/T.T.
7.11E-01	2.79E-02	6.87E-01	4.98E-01	1.39E-01	8.87E-02	3.92E-02	1.40E-01	7.64E-01	7.64E-01
2.29E-03	4.84E-01	0.00E+00	8.75E-06	1.35E-05	1.23E-05	1.03E-01	4.67E-04	1.90E-02	1.90E-02
4.65E-18	1.15E-03	1.48E-12	1.51E-14	1.25E-09	9.40E-12	3.01E-04	2.25E-10	5.58E-10	5.58E-10

Table D - 5 Camera Comparison, Statistical Tests for Straight Trajectory

Straight Trajectory Camera Comparison Statistical test H									
Area	Length	A/L	Max. D.	Str.Cor.	Acc. Cor.	Brk. Cor.	Max. Sp.	Av. Sp.	A/T
1	0	0	1	0	1	1	0	1	1
0	1	1	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

Straight Trajectory Camera Comparison Statistical test H									
Av. M. Sp.	SD. M. Sp.	Stops	T. Mov.	T. Stp	T. Run	T. Ini.	T.S./T.M.	T.S/T.T.	T.M/T.T.
1	1	1	0	1	1	0	1	1	1
0	0	0	0	1	0	0	1	1	1
0	0	0	0	0	0	0	0	0	0

Straight Trajectory Camera Comparison Statistical test P									
Area	Length	A/L	Max. D.	Str.Cor.	Acc. Cor.	Brk. Cor.	Max. Sp.	Av. Sp.	A/T
4.40E-02	5.97E-02	9.95E-02	5.65E-04	1.48E-01	6.46E-03	1.52E-02	2.19E-01	2.81E-02	2.11E-03
7.41E-02	9.06E-05	1.39E-03	3.96E-02	3.86E-01	1.74E-01	6.21E-01	5.12E-01	3.56E-01	6.43E-02
8.92E-01	6.36E-01	4.42E-01	6.65E-01	9.36E-01	5.43E-01	4.26E-01	8.56E-01	7.35E-01	7.87E-01

Straight Trajectory Camera Comparison Statistical test P									
Av. M. Sp.	SD. M. Sp.	Stops	T. Mov.	T. Stp	T. Run	T. Ini.	T.S./T.M.	T.S/T.T.	T.M/T.T.
3.57E-02	1.84E-03	1.38E-07	9.23E-02	1.11E-06	1.54E-02	3.77E-01	1.44E-06	6.80E-07	6.80E-07
7.75E-01	2.47E-01	5.37E-01	6.94E-01	8.48E-03	4.56E-01	6.76E-01	3.75E-03	6.49E-03	6.49E-03
6.95E-01	7.97E-01	3.56E-01	7.09E-01	2.29E-01	8.18E-01	1.74E-01	2.03E-01	2.03E-01	2.03E-01

Table D - 6 Camera Comparison, Statistical Tests for Reverse Trajectory

Reverse Trajectory Camera Comparison Statistical test H									
Area	Length	A/L	Max. D.	Str.Cor.	Acc. Cor.	Brk. Cor.	Max. Sp.	Av. Sp.	A/T
0	1	0	0	0	0	1	0	0	1
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0

Reverse Trajectory Camera Comparison Statistical test H									
Av. M. Sp.	SD. M. Sp.	Stops	T. Mov.	T. Stp	T. Run	T. Ini.	T.S./T.M.	T.S/T.T.	T.M/T.T.
0	0	0	0	1	0	0	0	0	0
0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	0	0

Reverse Trajectory Camera Comparison Statistical test P									
Area	Length	A/L	Max. D.	Str.Cor.	Acc. Cor.	Brk. Cor.	Max. Sp.	Av. Sp.	A/T
3.86E-01	3.74E-04	5.74E-01	4.81E-01	6.90E-02	4.30E-01	2.04E-02	8.76E-01	8.08E-01	8.19E-03
4.91E-01	3.18E-01	5.37E-01	8.59E-01	3.59E-01	7.43E-01	1.19E-01	8.44E-01	1.18E-01	2.36E-01
9.11E-01	1.68E-01	7.55E-01	9.80E-01	9.13E-01	5.16E-01	6.22E-01	6.31E-02	2.04E-01	5.16E-01

Reverse Trajectory Camera Comparison Statistical test P									
Av. M. Sp.	SD. M. Sp.	Stops	T. Mov.	T. Stp	T. Run	T. Ini.	T.S./T.M.	T.S/T.T.	T.M/T.T.
8.98E-01	3.06E-01	1.24E-01	2.24E-01	2.42E-02	6.80E-02	5.35E-01	9.02E-02	7.97E-01	7.97E-01
9.14E-01	1.07E-01	1.50E-01	6.86E-01	2.74E-01	9.48E-01	6.46E-01	1.96E-02	1.99E-01	1.99E-01
2.18E-01	3.32E-01	6.70E-01	3.71E-01	2.67E-01	3.55E-01	6.57E-01	9.94E-01	4.68E-01	4.68E-01

Table D - 7 Camera Comparison, Statistical Tests for Path Following

Path Following Camera Comparison Statistical test H									
Area	Length	A/L	Max. D.	Str.Cor.	Acc. Cor.	Brk. Cor.	Max. Sp.	Av. Sp.	A/T
0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0

Path Following Camera Comparison Statistical test H									
Av. M. Sp.	SD. M. Sp.	Stops	T. Mov.	T. Stp	T. Run	T. Ini.	T.S./T.M.	T.S/T.T.	T.M/T.T.
0	1	0	0	0	0	1	0	0	0
0	0	0	0	0	0	1	0	0	0
0	0	0	0	0	0	0	0	0	0

Path Following Camera Comparison Statistical test P									
Area	Length	A/L	Max. D.	Str.Cor.	Acc. Cor.	Brk. Cor.	Max. Sp.	Av. Sp.	A/T
1.07E-01	3.82E-01	2.17E-01	1.77E-02	8.28E-01	8.98E-01	1.48E-01	9.87E-01	8.05E-01	4.33E-01
5.03E-02	1.00E-01	2.55E-01	1.99E-01	5.04E-01	8.76E-01	3.39E-01	3.93E-01	4.76E-01	5.92E-03
9.39E-01	8.45E-01	9.03E-01	3.58E-01	4.20E-01	2.84E-01	4.59E-01	3.56E-01	9.74E-02	7.68E-02

Path Following Camera Comparison Statistical test P									
Av. M. Sp.	SD. M. Sp.	Stops	T. Mov.	T. Stp	T. Run	T. Ini.	T.S./T.M.	T.S/T.T.	T.M/T.T.
7.11E-01	2.79E-02	6.87E-01	4.98E-01	1.39E-01	8.87E-02	3.92E-02	1.40E-01	7.64E-01	7.64E-01
7.30E-01	2.58E-01	3.40E-01	2.72E-01	3.35E-01	6.61E-01	2.45E-02	5.58E-01	8.05E-01	8.05E-01
4.33E-01	5.16E-01	2.49E-01	6.02E-01	1.77E-01	2.34E-01	6.07E-01	1.51E-01	1.14E-01	1.14E-01

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