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DEVELOPMENT OF AN OFF-ROAD GROUND VEHICLE PLATFORM FOR TELEOPERATION

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ABSTRACT

This thesis deals with the teleoperation of a ground vehicle, specifically the construction processes associated with actuating the vehicle and the computer systems necessary for its control. The primary objectives of this thesis are to present the successes and failures of developing a ground vehicle platform to be used for teleoperation, to outline the computer architecture needed for wireless control of the vehicle, and to convey the lessons that were learned along the way.

Development of a teleoperated vehicle is a multi-faceted project. One of the most important steps to a successful teleoperated vehicle is the construction of a capable actuation system. Once the actuation system is designed and constructed, the system must be given commands to govern its performance, and hence the performance of the teleoperated vehicle. With the development of an off-road vehicle platform, the groundwork is laid for significant advances in teleoperation and the entire field of unmanned vehicle technology.

for my parents

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I would first like to thank Dr. Sean Brennan for his supervision throughout this thesis and his dedication to helping me excel. He has been a great mentor and a large part of my development as a successful student.

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Chapter 1

Introduction

This thesis deals with the teleoperation of a ground vehicle, specifically the construction processes associated with actuating the vehicle and the computer systems necessary for its control. The primary objectives of this thesis are to present the successes and failures of developing a ground vehicle platform to be used for teleoperation, to outline the computer architecture needed for wireless control of the vehicle, and to convey the lessons that were learned along the way.

The intent of this project is to develop a capability to research unmet challenges of remotely-guided vehicles. Such vehicles are crucial for future unmanned applications including lunar and Mars travel, remote operation of vehicles in dangerous situations such as hostile military environments, emergency evacuations, and mining, and automation of mundane tasks like farming. These areas are reviewed in detail below.

As an immediate goal, the project began with a vision of remotely-controlling an off-road go-kart at the Pennsylvania Transportation Institute (PTI) test track from the immersive driving simulator located on-campus at Penn State University. Such a project was not as simple as wiring the go-kart to a standard radio-control transmitter, given the several miles separating the driving simulator from the test track and the lack of an actuation system on the go-kart. Much research and planning would have to be done first in order to accomplish teleoperation of the vehicle. An actuation system had to be constructed and the vehicle had to be equipped with a computer system to support wireless control.

1.1 Background on Teleoperation

Fong and Thorpe define teleoperation as simply “operating a vehicle at a distance.” They allow the term “teleoperation” to include some form of vehicle autonomy, where the operator mainly supervises the vehicle in action rather than controlling it, although other authors disagree on this definition. Teleoperation is often used for vehicle control in hard-to-reach environments or to minimize mission expenses, and frequently in situations that are deemed too dangerous for human presence. Fong and Thorpe also identify characteristics of vehicle teleoperation that are crucial to its success, namely reliable navigation, capable motion command generation, and localized sensor data (Fong and Thorpe).

Teleoperated vehicles are just one category of “unmanned ground vehicles,” or UGVs. A second category of UGVs are autonomous vehicles, defined by Gage as vehicles that “determine their own course using onboard sensor and processing resources.” Gage differs from Fong and Thorpe in his definition of teleoperated vehicles, reserving the term for vehicles solely controlled from an external operator with no form of autonomy involved. He uses the term “supervisory control” for any sort of vehicle that combines commands from external operators and onboard sensors to navigate (Gage). Regardless of the definitions however, both teleoperated vehicles and autonomous vehicles share many technological characteristics, including similarities in vehicle actuation and computer architecture. Motivation for increased research within the two categories remains very similar as well. There are a wide range of interests for advancing UGV technology, particularly from the automotive industry and aerospace and defense industries.

1.2 Motivation for Research from the Automotive Industry

According to the U.S Department of Transportation, over 6,000,000 highway vehicle accidents were reported in the United States each year between 1990 and 2005 (Transportation Accidents by Mode). On average, over 40,000 fatalities were reported for each of these years due to highway accidents, with the number of injured passengers even higher (Transportation Fatalities by Mode). With such staggering statistics, it is easy to see why the government and automotive industry are interested in researching intelligent vehicles.

A major goal of the Department of Transportation's Automated Highway System program is to implement partially-automated, and eventually fully-automated, vehicle control technologies to improve the safety and efficiency of U.S highways (Gage). Intelligent transportation systems (ITS) are also being researched for economical and environmental reasons, notably to reduce energy consumption, and even to improve upon automobile comfort and convenience (Schmidt) (Bertozzi, Broggi and Cellario). The ITS approach is an integrated approach that links vehicles, drivers, and embedded electronic and computer systems and can be considered a subset of UGV and autonomous vehicle research (Bertozzi, Broggi and Cellario).

Reduced congestion, better fuel economy, and increased awareness of other vehicles and the surrounding environment are all objectives of the ITS initiative that will be addressed as UGV technology improves. Passenger vehicles may not qualify as “unmanned ground vehicles,” but the advancements in UGV technology can be implemented within the automotive industry as within the aerospace and defense industries. However, the aerospace and defense industries have slightly different intelligent vehicle applications in mind, whether partially or fully autonomous.

1.3 Motivation for Research from the Aerospace and Defense Industries

Within the aerospace and defense industries, human involvement in hazardous or life-threatening situations on land is quickly being replaced by UGVs (Pezeshkian, Nguyen and Burmeister). These situations typically call for some form of reconnaissance or surveillance, although UGVs are beginning to see action in military combat situations as well. The urgency to implement UGVs for military applications increases with each soldier casualty. The U.S. Department of Defense has demanded UGV research ever since the release of a congressional mandate stating that one-third of military ground vehicles must be unmanned by 2015 (McWilliams, Brown and Lamm).

Aerospace and defense industry examples of UGVs include military robots used for explosive ordnance disposal (EOD), teleoperated dune buggies for Reconnaissance, Surveillance, and Target Acquisition (RSTA), and a range of NASA exploration rovers (Gage) (McWilliams, Brown and Lamm). Space exploration rovers have been in existence for decades, as rovers drastically reduce the cost of spaceflight missions, eliminating the need for manned spacecraft and complex, costly life-support systems (Gage). Thus, space exploration continues to be an area of motivation for unmanned ground vehicles.

Aside from military vehicles and exploration rovers, Fong and Thorpe identify a third classification of UGVs known as hazardous duty vehicles. Not unlike military and space vehicles, hazardous duty vehicles are employed in situations that pose extreme danger to humans, often related to chemical or toxic waste removal (Fong and Thorpe), mining operations, or bomb disposal.

No matter the application, one common theme is present throughout the industries: reduce human involvement. Reduction in human involvement means the reduction of potentially dangerous situations and improvement in safety and comfort. As a result, operational efficiency and capability increase, and mission expenses and human fatalities decrease.

1.4 Outlook and Objectives

Nielsen, Goodrich, and Ricks suggest that perhaps the greatest reason for poor navigation of teleoperated vehicles to date has been the lack of situational awareness, or “telepresence,” for the operator (Nielsen, Goodrich and Ricks). Earlier it was stated that the third crucial characteristic for teleoperation is localized sensor data, due to the necessity to convey the vehicle’s surroundings to the operator. Based on past experiences however, Nielsen, Goodrich, and Ricks present that operators usually have less than adequate knowledge of the vehicle's environment. It is often difficult for operators to fully extract an understanding of the environment from the video images that so many robots transmit (Nielsen, Goodrich and Ricks). Video data is an integral component of direct interfaces, the most common type of teleoperation interface, despite their tendency to be problematic. Direct interfaces typically feature an operator watching video from the robot while giving commands with hand-held controllers. Loss of situational awareness, inaccurate attitude judgment, and poor obstacle detection are all common faults with direct interfaces (Fong and Thorpe). As a result, operators turn to navigating the vehicle at very low speeds, which can be a tiresome process that demands extreme caution (Babic, Budisic and Petrovic).

There have been recommendations for improving this issue with teleoperated vehicles, including increased use of maps, better sensor fusion, and providing operators with more spatial information (Nielsen, Goodrich and Ricks). The implementation of a more sophisticated interface with higher data quality has been suggested by numerous researchers (Babic, Budisic and Petrovic). Specifically, this thesis focuses on laying the groundwork for these types of improvements. By developing a vehicle and interface where telepresence of the operator can be dramatically improved, successfully teleoperation is much more probabilistic.

Fong and Thorpe state that the use of direct interfaces works best when real-time control of the vehicle is needed and a high-bandwidth, low-delay communication route is accessible (Fong and Thorpe). However, this often means that teleoperation over a long distance is very difficult, as data transfer becomes less reliable. Bandwidth limitations are limitations that cannot be altered and must be factored into the design of the system (Grange, Fong and Baur). In 2001, a publication entitled “UGV Lessons Learned” identified “communications are not dependable” as one of the top ten lessons learned. The authors urged researchers to develop systems that reduced communication requirements and emphasized vehicles thinking for themselves (Blackburn, Laird and Everett). Overreliance on communications is a key pitfall for successful teleoperation.

Thus, it follows that an optimal teleoperation system conveys high-quality environmental data to the operator while limiting information transmission. The goal of this thesis is to develop a platform where such a system is achievable. While data fidelity is limited by communication bandwidth restrictions, it can be improved by increasing the fidelity of a virtual environment in which an operator controls the vehicle. Rather than continuously transmitting video images from robot to operator, navigating the robot in a structured, known environment reduces the dependency on large data transmission. Knowledge of its surroundings can be embedded in the vehicle’s computer architecture, as well as the operator’s interface. The operator, if equipped with adequate spatial information and terrain characteristics, can navigate without hesitation or lack of confidence in the information conveyed in video images. Some level of local autonomy would undoubtedly be involved, as the robot could react to discrepancies between the environment it “sees” and the environment it expects to see. Even by only conveying these discrepancies to the operator, the total amount of data transmitted is significantly reduced. As a result, a high-fidelity system is attainable that increases the situational awareness of the operator and depends little on data communication.

Ultimately, the objective of this work is to control the ground vehicle developed throughout this project via the immersive driving simulator located at PTI on-campus at Penn State University (see Figure 1.1). The vehicle itself will be navigating a known environment several miles away at the PTI test track. Both the vehicle and simulator will consult a LIDAR map of the region to successfully drive at high speeds without hesitation or collision. Preliminary developments of the vehicle and computer architecture needed for its control are presented in this thesis.

Figure 1.1: The Immersive Driving Simulator at PTI (Courtesy of PTI)

The outline of the thesis is as follows: chapter two presents a brief history of intelligent vehicle research to this point, chapter three discusses the actuation of the ground vehicle and its construction, chapter four presents the radio control phase of the vehicle's development, and chapter five outlines the implementation of computer systems onto the vehicle. The outcomes of the thesis are summarized in the conclusion section, and future work is listed for later reference.

Chapter 2

History of Teleoperated and Autonomous Ground Vehicles

It is appropriate for this thesis to present a brief history of teleoperated and autonomous ground vehicles. Examining UGV research of the past helps to understand the state of current research and gives a clearer picture of the motivation for continuing to advance the field. Presented in this section are some examples of development efforts that were regarded as state-of-the-art during their respective time periods.

Many consider the earliest demonstration of mobile robots to be the wheeled platform named SHAKEY, researched at the Stanford Research Institute and funded by DARPA in the 1960's (Gage). SHAKEY was the first development effort to show some form of path planning and automated navigation, using its onboard TV camera and ultrasonic range finder to explore (Meyrowitz, Blidberg and Michelson). Stanford University continued in the 1970's to be a leader in robot mobility, with the work of Hans Moravec and his Stanford Cart. The Cart moved through cluttered environments at a very slow speed (one meter every 15 minutes), using a TV camera vision system (Gage).

In 1981, Moravec moved to Carnegie Mellon University and developed the CMU Rover, a more capable robot able to handle more complex perception and control experiments (Meyrowitz, Blidberg and Michelson). Moravec's robot work paved the way for significant intelligent vehicle advancements at Carnegie Mellon University, highlighted by the Navlab projects in the 1990's, presented later in this section.

Space exploration rovers are perfect examples of teleoperated ground vehicles that were advanced for their time. As early as the 1970's, Soviet moon rovers roamed the lunar surface collecting samples and performing other scientific tasks, all under the command of external operators (Fong and Thorpe). Since these first vehicles, NASA has developed their own teleoperated rovers, including the Dante, Nomad, Sojourner, and recent Mars rovers that have long exceeded their life expectancy.

It can be argued that the beginning of full-size autonomous vehicles can be dated back to the 1960's and 70's when The Ohio State University began studies on vehicle guidance and control as part of the Automated Highway System (AHS) research efforts. For the first time, researchers demonstrated fully automated driving at highway speeds (30 m/s) with wire-guided steering and longitudinal and car-following control algorithms (Fenton and Mayhan). Automated merging and lane change maneuvers were also demonstrated. However, researchers conceded that the development of automated highway operations would have to wait for significant advances in sensor technology and communications.

By 1977, the Tsukuba Mechanical Engineering Lab in Japan developed what they considered the "first intelligent vehicle." This vehicle (see Figure 2.1) was capable of tracking the white lane markers on the road using machine vision technology (Association). The vehicle followed these markers for 50 meters at speeds of up to 30 km/h (Schmidhuber).

Figure 2.1: The Tsukuba Intelligent Vehicle (Courtesy of Advanced Cruise-Assist Highway System Research Association)

A huge success for military teleoperation came in the 1980's with an effort from the Naval Oceans Systems Center (NOSC) that focused on reconnaissance, surveillance, and target acquisition (RSTA). The Advanced Teleoperator Technology (ATT) TeleOperated Dune Buggy was developed at NSOC Hawaii, featuring a Chenowth dune buggy equipped with a vision system and mounted weapons. This project draws many parallels to the work of this thesis, as the dune buggy demonstrated the ability to cross natural terrain at high speeds while being controlled remotely (Gage). The success of the ATT dune buggy led the NOSC to continue work on unmanned ground vehicles, producing the new TeleOperated Vehicle (TOV) that was tested in 1988. The TOV was a HMMWV used for long-range RSTA (up to 30 kilometers away) that required a complex control system to integrate its sensors and actuation system (Gage). The ATT dune buggy and TOV are pictured in Figure 2.2. Numerous other military vehicles followed these initial two, demonstrating waypoint-based navigation and navigation by TV images sent to remote operators.

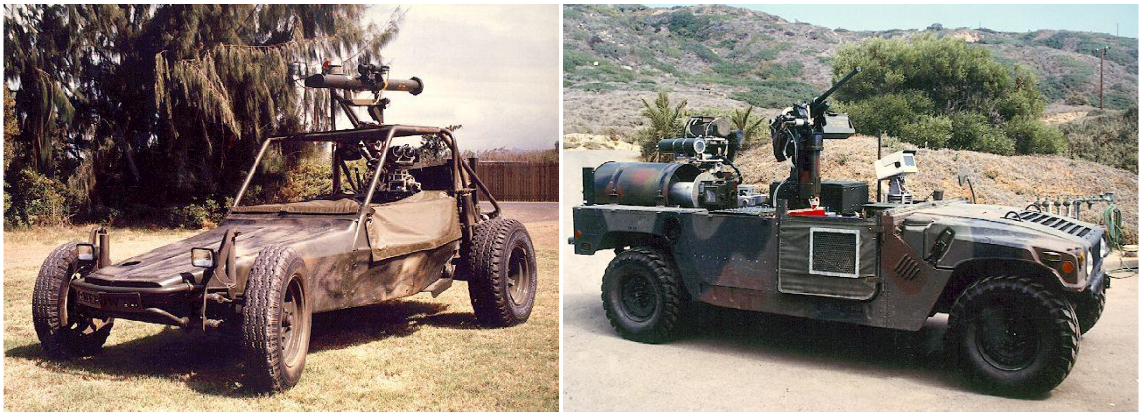

Figure 2.2: The NOSC ATT Dune Buggy (left) and TOV (right) (Courtesy of the Space and Naval Warfare Systems Command)

In 1987, the European Commission funded the EUREKA PROMETHEUS (PROgraM for a European Traffic with Highest Efficiency and Unprecedented Safety) project. More than one billion dollars was invested into driverless car technology up through 1995, making the PROMETHEUS project still the largest driverless car research and development effort ever. More than 13 vehicle manufacturers participated in the project, as well as many government and academic research groups (Bertozzi, Broggi and Cellario). The research group of Ernst D. Dickmanns at the University of Bundeswehr in Munich (UniBwM) made significant contributions to the project and became the leader in intelligent vehicle technology at that time.

Dickmanns is considered by many to be a pioneer in driverless vehicles, and more specifically, dynamic vision as it relates to driverless vehicles. His research group at

UniBwM is credited with developing the world's first autonomous vehicles, vehicles that used saccadic vision, Kalman filtering, and parallel computers ("transputers") to navigate on their own (Schmidhuber).

Figure 2.3: Ernst Dickmanns and the VaMoRs and VaMP (Courtesy of the University of Bundeswehr, Munich)

The first autonomous vehicle developed by the group was the "Vehicle for autonomous Mobility and Computer Vision," known as VaMoRs, shown in the center of Figure 2.3. The vehicle was a Daimler Benz van equipped with an image processing system and computer control of the throttle, brake, and steering. In 1987, the VaMoRs completed 20 km of autonomous driving in a traffic-less environment at 96 km/h. Dickmanns and his group developed a lane detection system called CRONOS, and by 1991, VaMoRs demonstrated the ability to recognize obstacles and drive on public roads with traffic (Wunsche).

The VaMoRs – Passenger Car, also known as VaMP, is shown on the right of Figure 2.3. This vehicle was Dickmanns's second highly-significant intelligent vehicle. The VaMP was a Mercedes Benz 500 SEL that used four cameras to navigate with vision-based control. The system was capable of detecting up to 12 other objects, usually other vehicles, at any given time. In 1994, the VaMP exhibited autonomous three-lane highway driving on Autoroute A1 in Paris, keeping lanes and safe following distances at speeds up to 130 km/h. By 1995, VaMP completed a 1758 kilometer trip that was 95 percent autonomous. The trip included over 400 autonomous lane change maneuvers and speeds up to 180 km/h (Wunsche).

The same year (1995) that VaMP drove over 1500 kilometers on Paris highways, Dean Pomerleau and Todd Jochem of the Robotics Institute at Carnegie Mellon University completed their "No Hands Across America" trip. The two researchers drove from Pittsburgh to San Diego in Navlab 5, a 1990 Pontiac Trans Sport capable of steering itself, shown in Figure 2.4. Navlab 5 autonomously performed 98.2 percent of the steering required for the cross-country journey, but the throttle and brake were human controlled (Pomerleau and Jochem, No Hands Across America). Pomerleau and his research group developed the RALPH (Rapidly Adapting Lateral Position Handler) computer program to steer the vehicle, a program that inferred road location from video images (Pomerleau, RALPH: Rapidly Adapting Lateral Postion Handler). They also introduced a portable navigation platform known as PANS (Portable Advanced Navigation Support) that provided a computing base and sensor integration station for their vehicle. The platform was designed to be portable and transferrable, powered from the vehicle's cigarette lighter (Jochem, Pomerleau and Kumar). With the PANS, Pomerleau proved that an inexpensive, convenient, and portable robust computer system could be developed for intelligent vehicles.

Figure 2.4: The Navlab 5 (Courtesy of Carnegie Mellon University)

Developers from the University of Parma in Italy spent six days on a trip in 1998 testing their ARGO autonomous vehicle, a Lancia Thema equipped with a stereoscopic vision system. Two cameras mounted in the front of the vehicle processed gray images to extract road geometry and parameters of the surrounding environment, including other vehicles (Bertozzi, Broggi and Fascioli, The ARGO Autonomous Vehicle). The ARGO drove autonomously 94 percent of the time on the 2000 kilometer trip at an average speed of 90 km/h (McWilliams, Brown and Lamm). An outline of the autonomous journey and snapshot of the ARGO in action are shown in Figure 2.5. The ARGO had three different driving modes: manual, supervised, and automated. In both the manual and supervised mode, the vehicle assisted the human driver by warning of dangerous situations and even assuming control of the vehicle in the supervised driving mode (Bertozzi, Broggi and Fascioli, The ARGO Autonomous Vehicle).

Figure 2.5: The ARGO Autonomous Vehicle (Courtesy of the University of Parma)

Perhaps the most popular exhibitions of autonomous vehicles were the recent DARPA challenges, with the Grand Challenge in 2005 and Urban Challenge in 2007. Not only did these challenges grab the public interest, but they also represent the culmination of intelligent unmanned vehicle technology to this point. The vehicles from these competitions are the most sophisticated vehicles to date, clearly seen from their performances in the challenges.

The first DARPA Grand Challenge took place in March of 2004, but none of the vehicles of the 17 final teams completed the 140-mile desert course. Still, the race was a great success in gaining awareness for autonomous vehicle research. The Grand Challenge was attempted again in 2005, with the vehicles from five teams successfully finishing the course, navigating through a variety of desert terrains and driving autonomously for hours. Stanley, the Volkswagen Touareg R5 from Stanford University seen in Figure 2.6, claimed the two million dollar top prize after finishing the course in just less than seven hours (Seetharaman, Lakhotia and Blasch). Stanley featured a wide variety of sensors that fed into its navigation software, including lasers, radar, cameras, GPS, and an inertial measurement unit. Path planning and terrain mapping were accomplished with extremely complex algorithms (Thrun, Montemerlo and Dahlkamp).

Figure 2.6: Stanley (Courtesy of Stanford University) and Boss (Courtesy of Tartan Racing)

Most recently in November 2007, DARPA held the Urban Challenge. Unlike the Grand Challenge, the Urban Challenge consisted of driving in suburban streets with intersections, stop signs, parking lots, road hazards, and most intriguingly, other manned and unmanned vehicles. Autonomous vehicles from six teams successfully completed the course, with the grand prize credited to Carnegie Mellon University's Tartan Racing Team and their Chevrolet Tahoe named Boss (also shown in Figure 2.6) (Urmson, Anhalt and Bagnell). The Urban Challenge proved to be a leap in complexity for vehicle decision-making and navigation programs. Yet, the vehicles usually exhibited safe and controlled autonomous urban driving, perhaps implying that bringing automated vehicles to public roads is not too far in the future.

From the research efforts and intelligent vehicles presented above, it is clearly seen that both teleoperated vehicles and autonomous vehicles share a great deal of technology.

Both classifications of UGVs possess actuation systems, integrated sensors, and almost always, some form of computer software control. While the DARPA challenges illustrated that vehicles are capable of thinking and acting on their own, there is still an enormous amount of technological advancement that can be made in the field of unmanned ground vehicles. Hopefully by looking into past developments and recognizing the progression of UGV technology throughout the past few decades, current research becomes more inspired and gains better direction.

Chapter 3

Actuation of the Vehicle

As presented previously, Fong and Thorpe state that one of the three critical characteristics of ground vehicle teleoperation is capable and efficient motion command generation. Performance of the teleoperated vehicle is directed related to the vehicle's ability to move (Fong and Thorpe), and this correlation demonstrates the necessity of a robust and capable vehicle actuation system. Before actuation of the vehicle can begin, the vehicle's physical parameters are first examined.

3.1 Overview of the Go-Kart

The ground vehicle platform used for this thesis is a Fox Havoc M5 off-road go-kart, shown in Figure 3.1 below. The go-kart features a rear-mounted Subaru four cycle gasoline engine. The engine size is 126 cubic centimeters and outputs 5 horsepower; thus, the go-kart is capable of achieving top speeds of 26 to 28 mph. The go-kart itself has two seats, weighs nearly 600 pounds, and has a load capacity of 325 pounds. The rear axle has a disc brake and a dual wheel torque converter drive for increased performance on various terrains. For driver safety, an ignition kill switch is embedded within the steering wheel and the vehicle has a full roll cage. Details regarding the go-kart's steering and throttle control will be given in the sections below as the actuation process is outlined.

Figure 3.1: The Off-road Go-Kart Used as the Ground Vehicle Platform for Teleoperation

The first step in actuating the go-kart was determination of the actions input by a human driver to control the vehicle. There are three major actions that were identified: steering control, throttle control, and braking. Unlike a full-size production vehicle, the go-kart had no transmission, turn signals, headlights, or any other features that would require additional actions for its operation. As a result, actuation would only need to focus on the three major actions stated above. The lack of drive-by-wire or electronic controls that are becoming increasing popular on modern full-size production vehicles meant that each of the three input actions for the go-kart would have to be accomplished by a mechanical actuator.

3.2 Steering the Go-Kart

Steering the go-kart proved to be the most formidable aspect of the actuation system. To introduce the steering process, the go-kart's physical parameters related to the steering system are presented.

The steering system on the go-kart functions similarly to a common rack-and-pinion steering system. A solid shaft extends from the steering wheel to a cross-linkage that moves the wheels back and forth. However, rather than a rack-and-pinion connection, the steering shaft is connected to the cross-linkage with a cantilever steering bar, seen in Figure 3.2. As the steering wheel is rotated, the bar sweeps through the range of steering angles and translates this range into the range of front tire steering angles. Thus, the steering wheel angle directly corresponds to the front tire steering angle. If the steering wheel is turned 30 degrees clockwise, the front wheels will also turn 30 degrees clockwise. Milliken and Milliken refer to this 1:1 steering ratio as "the ultimate in fast steering," as it permits the driver to negotiate tight turns at high speeds with little steering wheel travel (Milliken and Milliken). The go-kart allows just less than 45 degrees of steering in either direction, limited by welded mechanical stops on the steering column. Both wheels always have the same steering angle, so Ackermann steering geometry is not present on this go-kart. Refer to Figure 3.3 for a view of the steering arm.

Figure 3.2: View of the Steering Column

Figure 3.3: View of the Steering Arm

With the go-kart stationary on a concrete surface, initial torque tests were performed to determine correct steering actuator size. A digital force gauge was used to measure the force needed to begin rotation of the steering wheel at various moment arms. The torque needed to rotate the steering wheel could then be found by multiplying the recorded force with its corresponding moment arm. The average torque was calculated to be 111.3 lb-in. This value, of course, would be dependent on a number of influencing factors, including tire inflation pressure, driving surface, speed, and weight inside the go-kart, among others. The torque needed to steer the vehicle would indefinitely fluctuate depending on the current states of the influencing factors for a given driving situation. As a general rule of thumb, it can be assumed that the torque required for steering a stationary vehicle will be higher than the torque required for steering a rolling vehicle.

Because of the 1:1 steering ratio and the inability of the steering column to rotate more than 90 degrees of total travel, it was decided that a limited-travel rotational servomotor would be implemented to steer the vehicle. This type of steering actuator is different than most steering actuators used on full-size production vehicles. Full-size production vehicles (that lack steer-by-wire capability) generally use DC motors for steering control. Most cars have steering ratios between 10:1 and 20:1, so the steering wheel rotates 10 to 20 times more than the front wheels, resulting in hundreds of degrees of steering wheel rotation. Only multiple-turn motors are suitable for this large range of motion, but for vehicles like the go-kart, a servomotor with limited travel is sufficient enough to cover the full range of steering wheel rotation.

The servomotor selected for steering control was the Tonegawa Seiko SSPS105, shown in Figure 3.4. The particular model that was chosen has +/- 45 degrees of travel and is capable of outputting 324 lb-in of torque. Such a servomotor is fairly easy to find, but the SSPS105 has specific advantages for this work because of its high torque-to-size ratio. The servo's maximum torque is enough to adequately steer the vehicle under all conditions, yet its small size is well-suited to the go-kart's limited space for steering actuator placement. The servo is approximately 5 inches by 5 inches by 2 inches in size and is easily secured in position with four mounting holes. It has a speed of 90 degrees per 0.9 seconds and requires 12 VDC for operation.

Figure 3.4: Tonegawa Seiko SSPS105 (Courtesy of Tonegawa Seiko)

With the servomotor in hand, the next task for steering actuation was to connect it to the steering column and mount it in place. However, directly connecting the servo to the steering column would be an unwise and dangerous mistake. Because this work involves an offroad go-kart traveling at high speeds and performing quick, jerky maneuvers, there is a constant risk of induced wheel lift and in extreme cases, vehicle rollover. Such an event includes the possibility of forcefully impacting the front wheels of the go-kart, causing them to turn quickly, thus inducing a very high torque back to the steering column. A torque incurred on the servomotor beyond its rating could strip its internal gearing or send a damaging current spike to the go-kart's onboard electronics. To alleviate this problem and protect the servomotor, the connection between it and the steering column must include some sort of torque-limiting mechanism. The mechanism would preserve the connection between the servo and steering column for relatively low-torque actions, such as steering and minor bump steer, but would sever this connection if a torque overload occurred.

Hobbyists face exactly the same type of torque-limiting problem with their R/C cars. They must protect their steering servos in the event of rollover, or maybe even more commonly, inexperienced hobbyists manually forcing the car's front wheels back and forth for fun. Most R/C hobby cars are equipped with a plastic "servo-saver" that absorbs any sort of torque overload on the steering system. These mechanisms are readily available and very inexpensive, but are only large enough to protect small hobby servos that usually output less than 150 oz-in. Servo-savers are too small and too delicate for this project, but provide a good model for what the torque-limiting device must accomplish.

Multiple friction-type devices were considered for their simplicity and inexpensiveness. "Friction-type devices" are classified here as devices that use friction to engage and disengage torque transfer. Such devices include tensioned rubber disks riding on each other, a V-belt pulley system, or some sort of friction clutch. All of these devices could be tensioned so that low torques would pass and higher torques would cause the disk/belt/clutch to slip. However, all of these devices would require timely experimentation to determine the correct tensioning for given torque values, and would most likely result in a loss of absolute positioning. Even slight slips in the system would produce an “offset” in the steering. Offsets would be acceptable for steering actuation systems that employed multiple-turn motors, but are undesirable for the task of steering a vehicle using the limited-travel servomotor that was purchased for this project.

Thus, torque-limiting methods that preserve absolute positioning were researched. A shear pin could be used to transmit the torque between the servo and steering column. This pin would act like a rigid connection at low torques and would snap instantaneously upon torque overloads. A second solution included an undersized timing belt that would function very similarly, snapping immediately upon torque overloads. Both of these solutions are inexpensive ways to eliminate possible offsets caused by slippage, but also require timely experimentation for correct pin/belt sizing.

Despite being more costly, mechanical torque limiters like those offered from Browning, Zero-Max, and R+W America proved to be the best choice. A model SK1 torque limiter from R+W America was selected for implementation on the go-kart. The SK1 provides a rigid coupling with zero backlash between the servomotor and steering column, maintaining absolute positioning (until overload occurs). Once overload occurs, steel balls inside the SK1 slide out of their tracks, disengaging the connection between the drive and driven components. R+W America initially set the SK1 for disengagement just above the torque capability of the servomotor at 40 N-m, equivalent to 354 lb-in. However, the SK1 can be adjusted for precise overload torque values anywhere between 20 and 60 N-m. A drawing view of the SK1 is displayed in Figure 3.5.

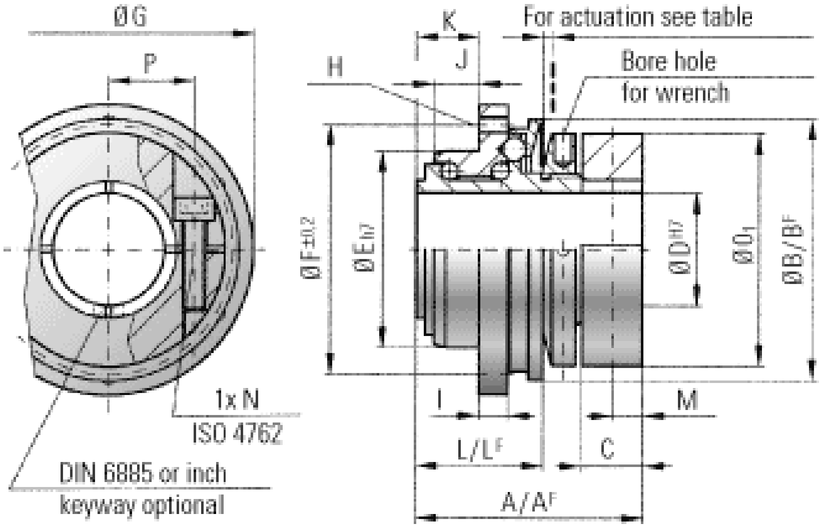

Figure 3.5: R+W America SK1 Mechanical Torque Limiter (Courtesy of R+W America)

Now that the torque limiter was acquired, connection to the steering column could commence. Initial objectives of the steering actuation system were as follows: preserve the steering wheel and make the actuation system removable so that a human driver could still operate the vehicle, provide an easy means for activating and de-activating the actuation system, and mount the system in such a way that would not hinder a human driver from sitting and operating the vehicle. The go-kart also had some physical restrictions on the flexibility of connecting the servomotor. The steering shaft was immovable and could only be accessed by removing the steering wheel. Only the few inches of shaft between the steering wheel and go-kart frame are available for mounting parts that needed to slide over the shaft.

With the objectives and physical restrictions in mind, it was decided that a timing belt pulley would be a cheap, adequate solution to connect the servo to the steering column. With the timing belt, the torque limiter and a pulley would mount on the steering column just below the steering wheel and the steering wheel could be preserved by extending the shaft. The belt would run to a parallel pulley mounted on the servomotor, held in place by a welded aluminum bracket. Figure 3.6 and Figure 3.7 give a SolidWorks view and a photo of the initial steering setup concept, respectively.

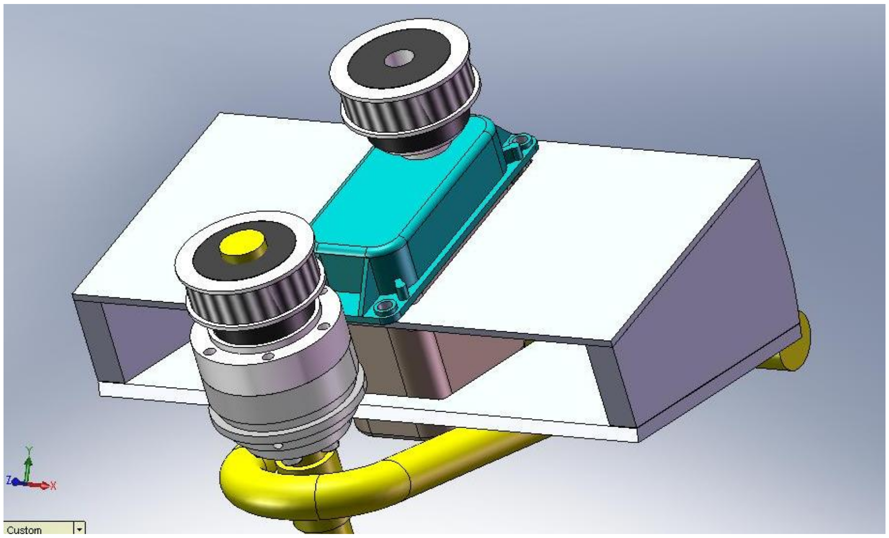

Figure 3.6: SolidWorks Model of Initial Steering Connection

Figure 3.7: Initial Steering Connection

After performing the necessary load and sizing calculations, a GT Power Grip timing belt was selected for this application. The belt had a 5 millimeter pitch, width of 15 millimeters, and 90 teeth. To keep the 1:1 steering ratio described earlier, two timing belt pulleys, with identical pitch diameters of 2.13 inches, were installed on the servomotor and torque limiter. An aluminum coupler was machined to attach the torque limiter and pulley, then the torque limiter was installed on the steering column. Positioning of the aluminum servo bracket was determined by calculating the center distance (5.51 inches) required for the timing belt and pulleys.

When the go-kart was lifted off the ground for the first radio-control tests (described in detail in Chapter 4), the initial steering setup performed as expected. The timing belt connection easily turned the front wheels to the desired steering angle, given that the wheels were off the ground. As soon as the vehicle was placed back on the ground, however, the static friction between the concrete surface and front wheels proved to be too great for the steering system. To output a larger torque to turn the wheels, the servomotor caused the welded aluminum bracket to flex significantly, resulting in poor tensioning of the timing belt. The timing belt proceeded to jump on the pulleys, losing absolute servo positioning and failing to steer the vehicle. The setup managed to steer the vehicle as it moved (due to the lower friction on the wheels as they rolled), but the belt frequently still jumped. Clearly, the steering system design needed revisions.

The lack of rigidity in the welded aluminum bracket was the prominent reason why the initial steering setup failed. The flexing in the bracket caused the timing belt pulley to loosen, thus rendering the center distance calculations for correct tensioning irrelevant and useless. A new design would need to feature a more rigid mounting bracket that could withstand the high torques needed to steer the vehicle. Also, eliminating the timing belt would increase the possibility of building a successful system because no tensioning problems would arise. The objectives of the steering system were revised to accommodate the necessary revisions in the steering system design. The new objectives focused more on steering system performance rather than accommodation of a human driver. The revised objectives were as follows: make the system as simple as possible to alleviate unnecessary design complications, provide a strong and rigid mount for the servomotor, and leave options open for the future installation of a steering wheel. Surely, these objectives better outlined a plan to provide capable and efficient motion command generation to the vehicle, which, as stated previously, is a critical aspect of successful teleoperation.

It was decided that the optimal solution for mounting the servomotor was to construct a large box frame that could anchor to various points on the go-kart. The anchor points would provide lateral stability to the frame to counteract the high torque output by the servomotor. The servomotor, with a machined aluminum coupler, could connect directly to the torque limiter installed on the steering column, removing the timing belt and related problems with tensioning, and drastically increasing the chances of successful steering. This alteration would also concentrically line up the servomotor axis and steering column axis, relieving the servomotor from any additional stresses caused by moments on its output shaft.

The box frame to mount the servo was constructed from aluminum profiles from 80/20 Inc. The profiles are easily cut to length and fastened with nuts and bolts also from 80/20 Inc., like a large industrial erector set. 80/20 provided specific advantages for the servomotor frame, given its high rigidity, adjustability, and versatility. SolidWorks model views of the servo mounting frame are shown in Figure 3.8 and Figure 3.9.

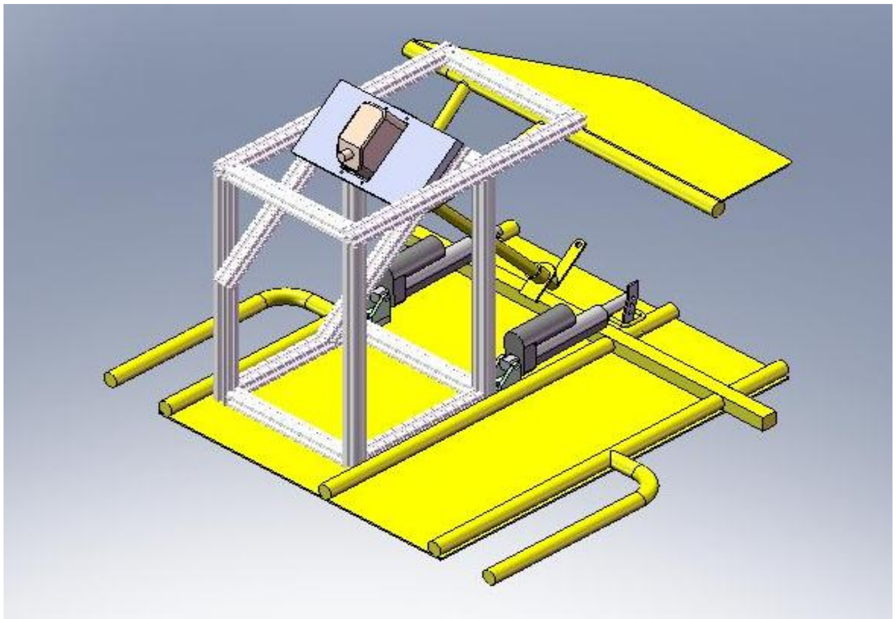

Figure 3.8: Isometric SolidWorks View of the Servo Mounting Frame

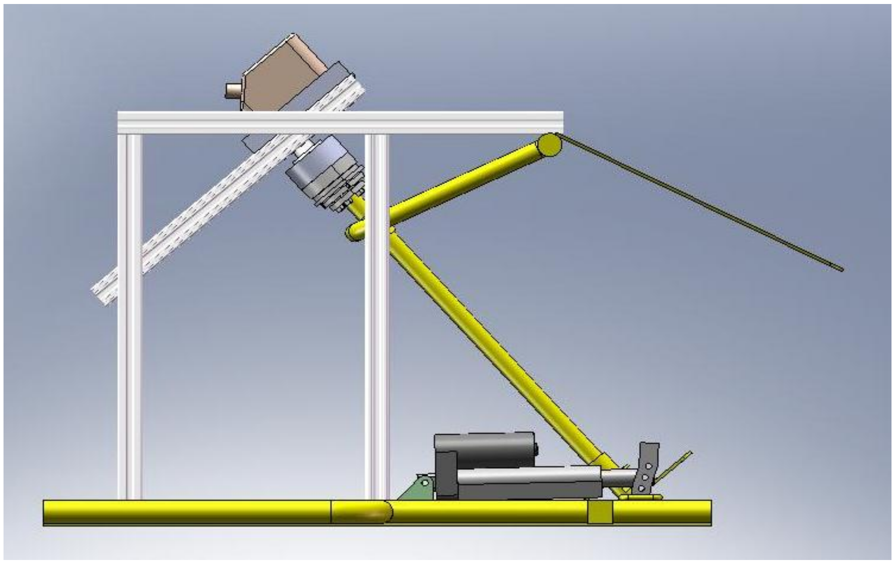

Figure 3.9: Right Side SolidWorks View of the Servo Mounting Frame

A 42 inch length of profile was secured laterally across the vehicle for additional support, shown in Figure 3.10. Not only did the new 80/20 frame provide strength and rigidity to the steering actuation system, it provides easy and numerous mounting options for radio-control electronics and computer systems.

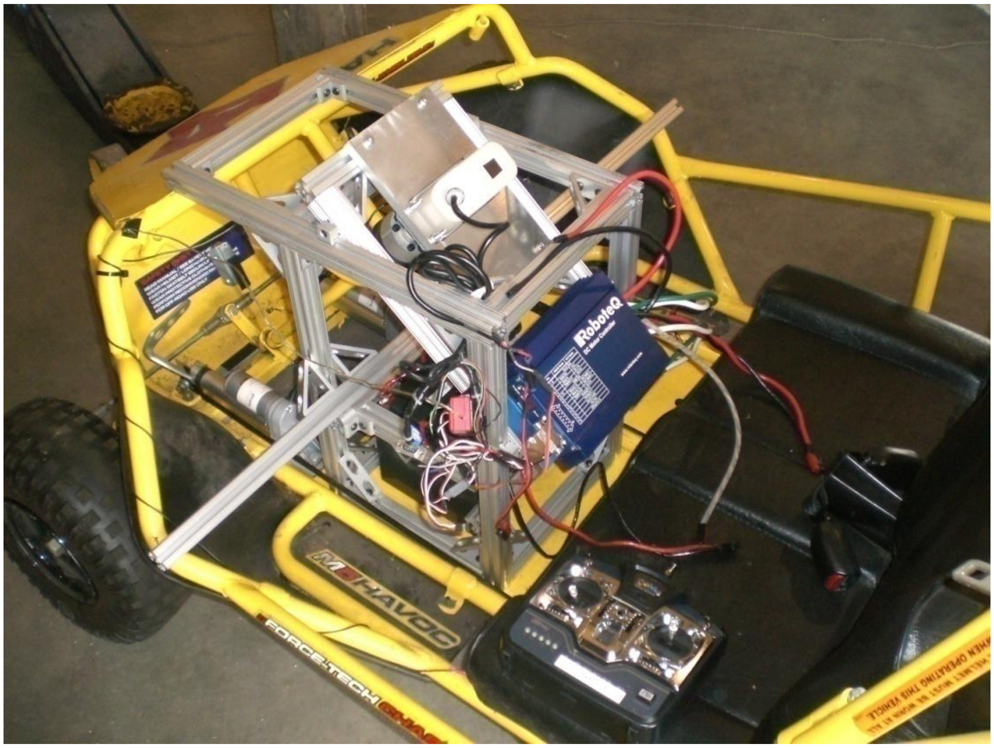

Figure 3.10: The 80/20 Steering Frame

Adjustability is a unique advantage of using the 80/20 frame. The frame is easily disassembled in case of improvements or modifications; for example, the addition of a steering wheel is a possible and practical future modification. The go-kart's original steering wheel can be reconnected with the timing belt that was eliminated earlier, once an adequate tensioning system is designed. Correctly tensioning the steering wheel would not be as critical as tensioning the servomotor, as the steering wheel could be turned multiple rotations, unlike the servomotor. Of course, frequent "jumping" of the belt would be undesirable, but the steering wheel would only be a secondary means of steering the vehicle. Teleoperation is only dependent on successful operation of the servomotor, not the steering wheel, and hence this tradeoff is acceptable.

The performance of the new steering actuation system was much better and more robust than the initial timing belt connection method. Radio-controlled, the servomotor was able to turn the front wheels on command, even with the vehicle stationary and with the wheels down on a surface. Full discussion of radio control of the go-kart is given in Chapter 4.

3.3 Throttle and Brake Actuation

Focus is now turned to the other two input commands to the vehicle: throttle and brake. Compared to the steering, actuating the throttle and brake is much more straightforward. As the throttle and brake pedals on the go-kart were very similar, their actuation systems were constructed very similarly. To introduce their actuation, the physical parameters of the pedals and cables on the vehicle are first presented.

The pedals that control the throttle and brake are mirror opposites of each other, with the throttle pedal mounted for the right foot and brake pedal mounted for the left foot. The pedals pivot at the floor of the go-kart from the hollow tube frame and rise 5 inches to the pads for the driver’s feet. Three quarter-inch mounting holes are positioned along the pedal at 1 inch, 1.5 inches, and 2 inches from the pivot point. Small metal stops are welded onto the tube frame to only permit approximately 30 degrees of travel for each pedal. A torsion spring centered around the pivot point returns each pedal to its initial position when no activation load is applied. Throttle control is regulated by a thin cable that attaches to the middle mounting hole on the pedal, while the brake line is a hard line that runs from the disc brake on the rear axle to the uppermost mounting hole on the pedal. Views of the throttle and brake pedals are shown in Figure 3.11 below.

Figure 3.11: Brake and Throttle Pedals (respectively)

As with the steering, initial force tests were executed to determine the correct actuator sizing for throttle and brake control. A digital force gauge was used to push each pedal through its entire stroke at 2 inches above its pivot. The maximum force needed to perform this task was recorded. Nearly all of the resistance to pushing the pedals was due to the torsion springs; the pedals and cables alone are practically effortless to engage. However, the tests were performed with the torsion springs in place to ensure the actuators would easily be able to control pedal position, no matter the setup. It was found that the throttle pedal needed a maximum force of 20.5 pounds to push through its stroke, and the brake pedal required a maximum force of 16.9 pounds.

To closely mimic the action of a driver’s foot pushing the pedals, it was decided that linear actuators would be used for the throttle and brake control. Desired specifications for the linear actuators were as follows: at least 2 inches of travel, capability to push through the entire stroke in less than one second, a force rating of higher than 25 pounds, and an overall size small enough to mount within the go-kart frame. Unlike the steering system, the force required to push the throttle and brake pedals would be virtually independent of outside factors. The driving condition, speed, driving surface, and other factors would have little to no effect on the difficulty of engaging the pedals, similar to full-size production vehicles.

Yet, there are still plenty of differences between actuating the go-kart pedals and full-size car pedals. Speed control in a car is done with an accelerator pedal that varies the acceleration of the vehicle as it is engaged. The go-kart has a throttle control pedal that varies the speed of the vehicle as it is engaged. The farther the pedal is pushed, the faster the vehicle travels, analogous to the throttle control on a motorboat or airplane. Braking in a car is sensitive to how fast the brake pedal is pushed by the driver. The quicker the pedal is engaged, the more braking force is applied, and the quicker the car slows down. In the go-kart, braking force is increased as the pedal stroke is increased. Thus, the farther the pedal is pushed, the more braking force the disc brake applies. These differences may seem subtle to a driver, but they are significant when determining the specifications for a capable and efficient actuation system.

Two identical model FA-35-S-12-3” linear actuators from Firgelli Automation were purchased to actuate the throttle and brake pedals. These actuators are rated at a maximum of 35 pounds of pushing force and 400 pounds of static holding force, adequate enough to provide successful position command to the pedals even with the torsion springs in place. They have a no-load speed of 2 inches per second and a total stroke extension of 3 inches. They are powered with 12 VDC and can be conveniently mounted with quarter-inch clevis mounts on each end, making mounting to the pedals a simple process.

Actuator mounting brackets were also purchased from Firgelli Automation to fasten the linear actuators to the floor of the vehicle. Thin raising plates were machined to position under the mounting brackets, lifting the linear actuators to a height where they could extend perpendicular to the moment arm of the pedals. With this configuration, the actuators would operate most efficiently. At first, limit switches were wired into the actuator power circuit to prevent the actuators from extending into the welded metal stops. These switches were later removed. Commanding the actuators into the mechanical stops harms neither the actuators themselves nor any electronic components. Thus, removing the switches was beneficial to the performance of the vehicle, as the throttle and brake control could both be pushed to the maximum level, as would be done by a human driver. Refer to Figure 3.12 and Figure 3.13 for views of the linear actuators mounted on the vehicle.

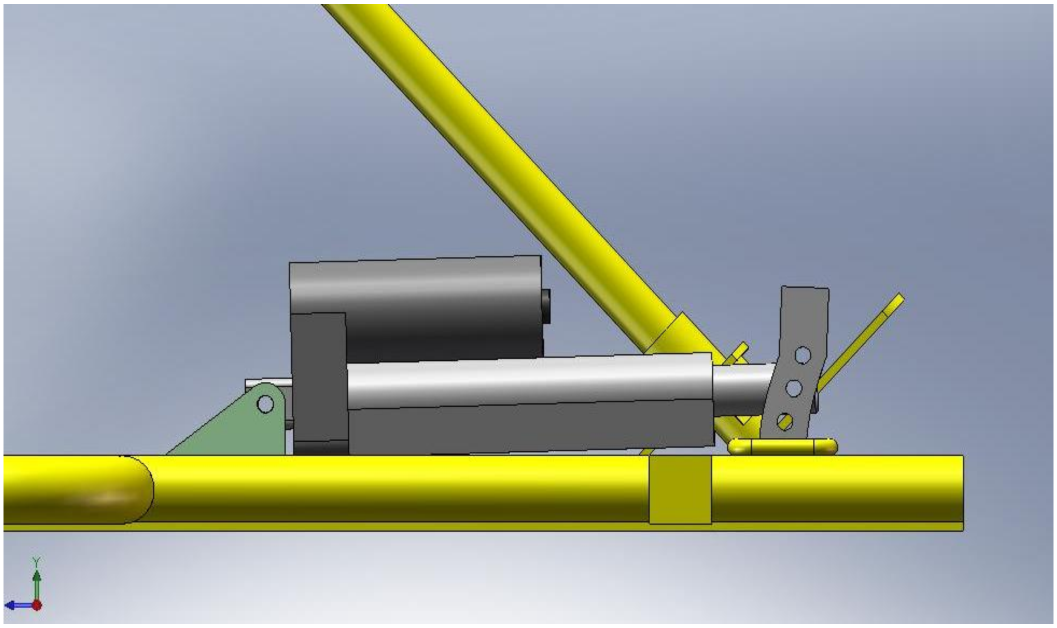

Figure 3.12: SolidWorks Model of Linear Actuators

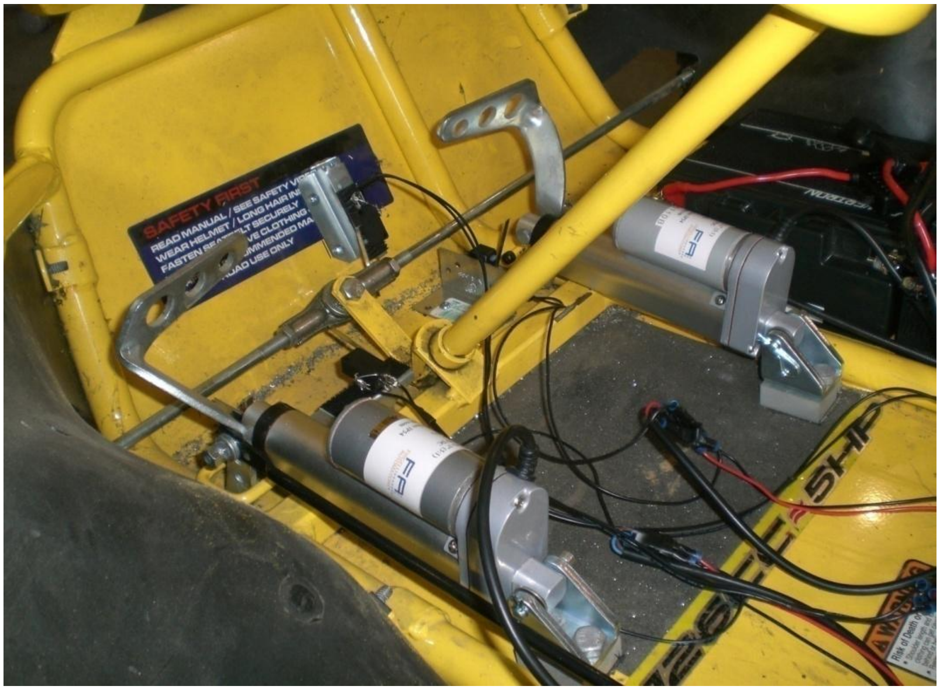

Figure 3.13: View of the Linear Actuators

It is important to note that the torsion springs were removed from the pedals as well. Their purpose is no longer needed with the linear actuators; the actuators must be commanded to extend and retract. Unlike a human foot, the clevis mounts on the linear actuators allow them to pull the pedals just as well as they can push the pedals. It is difficult and very unsafe for a human to pull the pedals back to a certain position, so the torsion springs do this job instead. The driver needs only to focus on pushing. With the springs removed, the linear actuators have very little resistance to controlling the position of the pedals. As a result, their actuation performance is bettered by allowing them to operate at higher speeds and lower motor currents.

Equipping the vehicle with an actuation system is a preliminary, but extremely important, step of developing a platform for teleoperation. Without capable and efficient actuation, teleoperation is not only destined to fail, but very difficult to even set in motion. All of the design iterations with the actuation system must be completed before beginning to develop a computer structure for wirelessly controlling the ground vehicle. In order to test the actuation system, a simple and safe testbed is needed. In the case of this off-road go-kart, radio control is a sufficient method for assessing the capability of the actuation system, while still closely monitoring the vehicle. The next chapter focuses on radio control of the go-kart, and the valuable lessons learned during its testing.

Chapter 4

Radio Control of the Vehicle

Radio control (R/C) of the vehicle is especially advantageous for testing because of its short setup time and relatively simple configuration. Before the vehicle was outfitted with the R/C components, though, objectives for this phase of the development were established. First and foremost, the goal of R/C control of the vehicle is to remotely command the steering, throttle, and brake, and ensure proper functioning of the entire actuation system. Other objectives are as follows: iterate the actuation design if necessary, target additional safety measures for the teleoperated vehicle, and prepare the system for computer control. Ultimately, the R/C testing may only be a stepping stone toward the goal of producing a teleoperated off-road vehicle. Thus, it is imperative that all possible debugging occur at this stage, when the system complexity is still low.

4.1 Overview of the Radio Control System

The first issue to address for controlling the vehicle is determining how to command the linear actuators. Commanding the steering servomotor is straightforward, as it includes a standard PWM (pulse width modulation) input. Conversely, the linear actuators lack some sort of position command input, and contain only leads running to their DC motors. Wiring the leads to a power source extends the actuator arm, and reversing the polarity of the leads retracts it. The best solution is to command the linear actuators with a DC motor controller. The motor controller can process the PWM input from the R/C signal, and command the actuators accordingly.

Figure 4.1: RoboteQ AX2850 Motor Controller (Courtesy of RoboteQ)

The motor controller used was a RoboteQ AX2850, shown in Figure 4.1. The controller has multiple input modes, including the R/C open-loop speed control that was used for this application. The throttle and brake linear actuators were wired to the two motor channels on the controller. An eight-channel HiTec R/C receiver was connected to the AX2850 via the serial port on its front face. A 12 VDC, 18 AH lead-acid battery served as the power source for the entire system. The steering servo was also powered by the battery, and its PWM input directly connected to the R/C receiver. Commands were given to the receiver with the corresponding HiTec dual joystick transmitter. A graphical outline of the R/C system is presented in Figure 4.2.

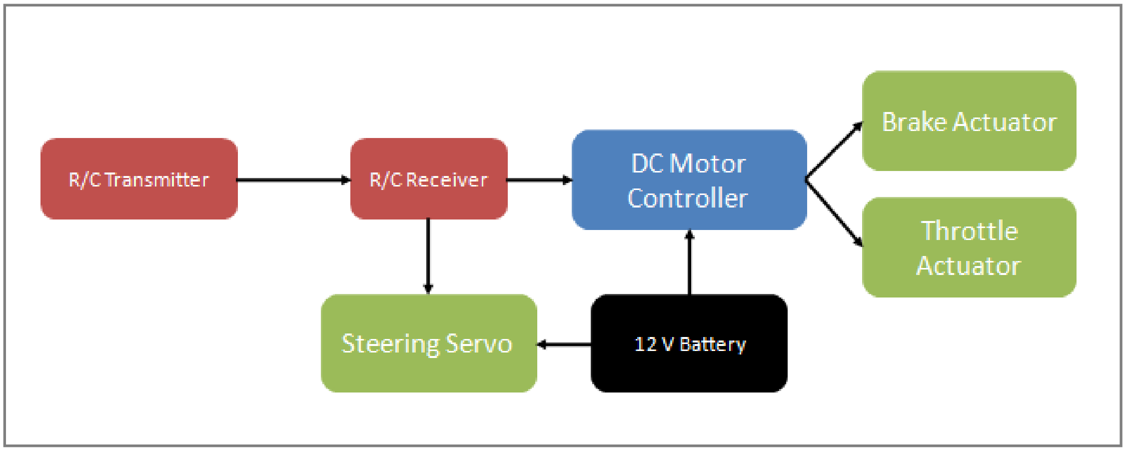

Figure 4.2: The System Layout for R/C Control

The R/C system was first implemented on the go-kart with the original timing belt steering setup. Radio control of the vehicle allowed for testing, making it possible to discover the problems with the timing belt tensioning. Other additional issues were discovered as well: the vehicle needed some sort of redundancy to prevent the system from losing control. There were a few concerns with leaving the R/C setup the way it was first installed. For example, if the go-kart traveled out of range of the radio transmitter with the throttle engaged, there would be no way to command its return. The vehicle would proceed to “run away,” immediately endangering other people and bringing about an extremely high probability of crashing into obstacles like trees or buildings, or navigating undesirable terrain features like ditches or steep slopes. Clearly, additional safety measures were needed.

4.2 Improvement Identification and Design Revision

Redundancy was needed in the radio control setup. Redundancy refers to the ability of a system to back itself up in case of a failure or malfunction. With the go-kart, redundancy was necessary in the command generation. The simplest way to implement redundancy into the R/C setup was to install DuraTrax Micro Failsafe Units (seen in Figure 4.3) between the R/C receiver and the actuation system. If the R/C receiver accidentally goes out of range, or the batteries drain below operation voltage, these small units command the actuation system to a specified "failsafe position," determined by the user. In this case, the throttle actuator fully retracts, the brake fully engages, and the vehicle holds a constant steering input to the right-hand side. With these failsafe units installed, the probability of a runaway vehicle is virtually eliminated.

Figure 4.3: DuraTrax Micro Failsafe Unit (Courtesy of DuraTrax)

In addition to the failsafe units, a TGN Ignition Kill Switch was wired to the ignition switch originally embedded in the vehicle's steering wheel. This switch can be toggled remotely with the R/C transmitter to kill the engine, but similar to the DuraTrax failsafe units, it also kills the engine upon sensing a signal loss. Now, if the go-kart travels out of range, the actuation system will return to a failsafe position and the engine will turn off. Levels of redundancy may sometimes seem unnecessary, but in reality, they represent a well-planned and safe system. The redundancy levels on the go-kart made it possible to test the performance of the R/C system with confidence that the vehicle would be controlled at all times.

When the 80/20 steering frame was constructed and the servomotor mounted in-line with the go-kart steering shaft, the R/C system was once again employed for testing. However, despite better steering performance, even more problems with the steering actuation were discovered. Only a few minutes into testing, the steering servomotor failed to respond to any input commands. Even with no resistance to turning, the servomotor was lifeless. The servomotor was subsequently removed from the vehicle and disassembled for failure analysis. Dissection of the mechanism unveiled the cause of the failure: the internal DC motor had overheated to the point where the wiring failed, most likely caused by a damaging amount of commanded current. Further investigation into the servomotor specifications revealed that the servomotor would damage itself if commanded into a hard mechanical stop. Installed on the go-kart, the steering shaft restricted the servomotor from exercising its full range of travel. Thus, whenever the vehicle was commanded into a hard left or right turn during testing, the servo would meet the mechanical stop, but continue to draw current to its motor to try to turn it farther. This constant increase in current proceeded to fry the motor coils, permanently damaging the servomotor and rendering it useless. The torque limiter did not prevent this type of damage, as it was preset to a torque value higher than the capability of the servomotor. Unfortunately, the steering system would have to be revised once again, this time with a new actuation method.

Depleting funds and fast-approaching deadlines made the decisions for the new steering actuator the hardest decisions to date. Replacing the damaged servomotor with an identical one was out of the question. The extended lead time for ordering another servomotor could not be accommodated, and it was also too expensive, especially for a product that failed so quickly in the application on a remotely-controlled vehicle. Instead, geared DC motors were researched. A motor of equivalent size and torque rating could be obtained at a significantly cheaper price.

The AME 226 Series gearhead motor (Figure 4.4) was purchased for use as the new steering actuator. With a maximum torque output of 36.7 N-m (325 lb-in) and nominal voltage of 12 VDC, it is practically the exact size of the servomotor. At its highest speed, the AME 226 spins at 96 rpm, making it capable of turning the steering shaft many times faster than the servomotor. However, the geared motor lacks a position feedback mechanism that the servomotor included. Servos are equipped with a potentiometer that measures the output shaft position and matches it to the input command. With the new geared motor, position feedback would have to be implemented using closed-loop control.

Figure 4.4: The AME 226 Series Gearhead Motor (Courtesy of AM Equipment)

Along with the separate position feedback, the geared motor did not include a command input like the servomotor had. There are only two leads running to the motor, similar to the linear actuators. Thus, this motor would also have to be commanded by an outside motor controller, and could not be wired directly to the R/C receiver like the servomotor. The RoboteQ AX2850 would suffice for this application, except that the two linear actuators already occupy its two motor channels. However, after careful consideration, it was decided that the new steering motor could replace the brake actuator on one of the channels. During the brief R/C testing phase, the brake actuator proved to function best in one of two states: fully on or fully off. The actuator ended up being wired to a simple toggle switch on the transmitter, rather than a joystick that commanded the input to the actuator proportional to its position. Such a basic use of the linear actuator did not demand the full capability of the AX2850 for its successful performance. Thus, a RCE220 Dual Relay Switch was purchased to control the brake actuator. This small, inexpensive switch can connect directly to the R/C receiver and process the input signal into a simple extend or retract command – perfect for braking the vehicle. With this change, the second channel on the AX2850 was freed for use with the geared steering motor.

The last area that was identified for improvement during R/C testing was the throttle control. With the throttle actuator wired in its initial setup (shown in Figure 4.2), the linear actuator would continue to extend when the transmitter joystick was pushed slightly forward, and retract fully back when the transmitter joystick was pulled even slightly back. This setup proved to be quite problematic for speed control. A more intuitive and convenient control method was desired. By implementing a position feedback device on the throttle pedal, the linear actuator can be commanded to a specific position, correlating directly to a specific go-kart speed. This position, and speed, would be proportional to the joystick position on the R/C transmitter. This method was also the exact kind of feedback control necessary for the steering motor. However, these control algorithms would have to be programmed into a computer that would then be installed on the vehicle, as the go-kart had no other “brains.”

In order for performance testing of the actuation system to resume, computer control was necessary. Installing such a system on the vehicle greatly increases its complexity, but allows for a wider range of safety measures, performance commands, and data measurement capabilities. The necessity for a more complex system is the topic of the next chapter: computer control of the vehicle.

Chapter 5

Computer Control of the Vehicle

Implementation of a computer on the vehicle was expedited because of the need to install simple control loops for the steering and throttle. The vehicle could not be successfully driven, and thus tested, until these control loops functioned correctly. As an added benefit, implementing a computer provides a convenient method for recording all types of data. Evaluation and assessment of a teleoperated vehicle is better accomplished with data that represents its performance. Gathering this data is much easier with a computer mounted directly on the go-kart.

5.1 Overview of the Computer Control System

All of the same components that were used for R/C control of the vehicle were preserved for computer control as well. Of course, the biggest and most important addition to the vehicle was the Athena single-board computer from Diamond Systems. For data acquisition, connected to the Athena was the Diamond-MM-32X-AT analog input/output module. Together, this computer features 32 single-ended or 16 differential analog inputs and four analog outputs. The analog inputs and outputs serve as the portals for data acquisition, necessary for both successful implementation of closed-loop control and recording vehicle performance data. The entire computer is less than five inches square by five inches tall, so it fits very well on the go-kart and can be easily secured to the existing 80/20 frame. The Athena supports the MATLAB/Simulink xPC Target software, which was used for this application. Communicating with the Athena through the xPC software provides a real-time communication link for implementation of the throttle and steering control loops and for capturing data. The xPC software is specifically advantageous because the control loops can be designed in Simulink with simple block diagrams, then built, compiled, and downloaded into the Athena. There is no need to write long computer language codes that are often troublesome for inexperienced programmers. With the computer in place, the actuation and control system can then be developed to rely on the computer’s analog inputs and outputs.

Before the rest of the computer control system was developed, objectives for this phase of the vehicle development were listed. First and foremost, the main goal of the computer control of the go-kart was to demonstrate the successful performance of the vehicle’s actuation system. Performance analysis is best accomplished with hard data validation, thus the second objective was to accurately record data related to the vehicle’s throttle and steering response. Yet, correct functioning of the throttle and steering actuators depended on the correct functioning of the closed-loop control needed for their command, bringing about the third objective. The final objective was to establish a computer architecture that would accommodate future changes and additions, including some degree of local autonomy, additional safety measures, and programs necessary for wireless control.

For this testing phase, it was desirable to keep the R/C transmitter as the method of generating commands to the actuation system. Thus, the first step toward computer control was developing a way for the computer to sense the R/C transmitter signal. Radio control signals are PWM signals, where the pulse width is proportional to the command. For example, moving the joystick all the way to the left sends a pulse with a one millisecond width. These pulses are repeated every 18 to 20 milliseconds. Moving the joystick all the way to the right sends pulses with 2 millisecond widths. Pulses of 1.5 milliseconds are representative of the middle position. Since the computer was equipped with analog inputs, a device is needed that reads the pulse width and sends a corresponding analog voltage to the computer. For most PWM applications, passing the signal through a low-pass filter is an adequate and simple method for converting to a DC voltage. However, the R/C transmitter only sends pulses every 20 milliseconds; passing this signal through a filter would yield only minor variations in voltage between “left” and “right” commands.

The best solution to convert RC signals to analog is to use a microchip like the BASIC Stamp or Microchip PIC. These chips are capable of counting the width of pulse inputs and outputting a PWM signal with a much higher duty cycle. This signal could then be filtered as described above. However, with deadlines approaching, there was not enough time to develop a circuit that included one of these chips. A faster, more convenient method was sought.

The quickest method for converting the R/C signal to a DC voltage was to use a mechanism that already implemented this conversion: a small Futaba servomotor. The servomotor directly accepts the R/C signal and turns its internal motor until it reaches the corresponding position. It uses its own potentiometer feedback to determine this position. Hence, the potentiometer outputs a voltage proportional to the R/C signal. By opening the servomotor and tapping its potentiometer, an analog voltage can then be brought to the computer's inputs. Because the computer needs to execute two control loops for the steering and throttle, two Futaba servos were modified.

The control loops for the steering and throttle actuators required their own position feedback devices. Potentiometers are the simplest feedback devices and ideal for this application. They provide an analog voltage proportional to their position, exactly the type of input that the computer requires. Connecting a potentiometer to the throttle pedal was straightforward: by extending the shaft on which the pedal pivots, the potentiometer was connected with a flexible coupler and fastened on an aluminum bracket to the floor of the vehicle. Connecting the steering potentiometer was not as simple since there were no available direct mounting configurations. Instead, the steering potentiometer had to be connected indirectly. The potentiometer shaft was inserted into a wide rubber wheel and positioned so that it rubbed on the coupler between the steering motor and torque limiter. The setup was held in place with a bracket made from 80/20 parts and mounted to the rest of the steering frame. A view of the steering potentiometer is given below in Figure 5.1.

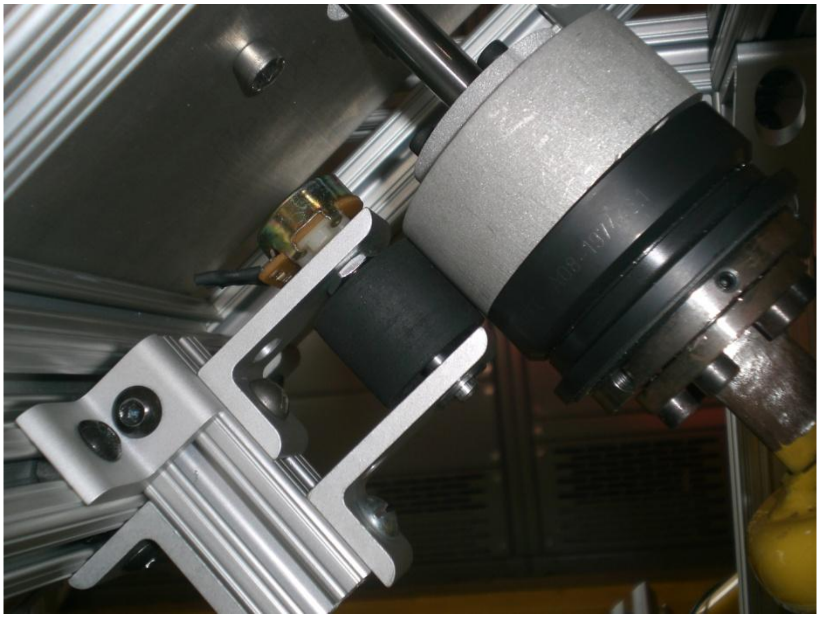

Figure 5.1: The Steering Feedback Potentiometer

With all the necessary components in place, the computer control program could now be developed. The control loops for the steering and throttle were diagramed in MATLAB/Simulink using the xPC Target blockset. Closed-loop proportional control algorithms were implemented for both steering and throttle control because of their simplicity and sufficiency. The more complex forms of derivative or integral control did not need to be included for the basic testing of this thesis. Figure 5.2 shows the control loops, as they were developed in Simulink. Notice that the control command includes a 2.5 V offset, as the analog inputs on the RoboteQ AX2850 use 2.5 V as their middle position. The analog inputs on the motor controller vary between 0 and 5 V, thus the control command was catered to this parameter.

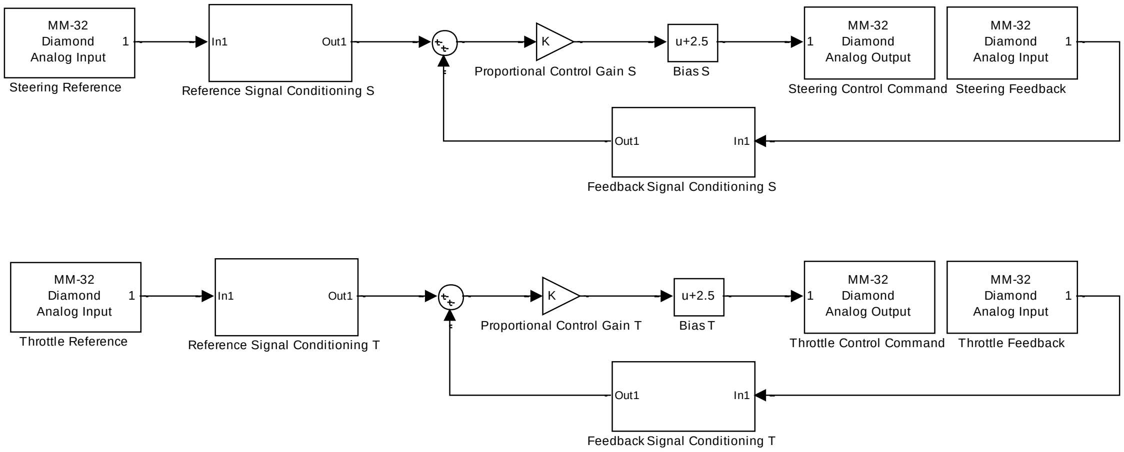

Figure 5.2: Closed-Loop Steering and Throttle Control

Before the entire computer control system was installed on the vehicle, correct functioning of the system was tested in the lab. When correct functioning was verified, the system was transferred to the go-kart for gain tuning and improved filtering for more accurate feedback information. The computer control system layout is presented in Figure 5.3. Other than the components needed for feedback control, the same components from the R/C control system were used. However, with the computer involved, the capabilities of the vehicle actuation increase dramatically.

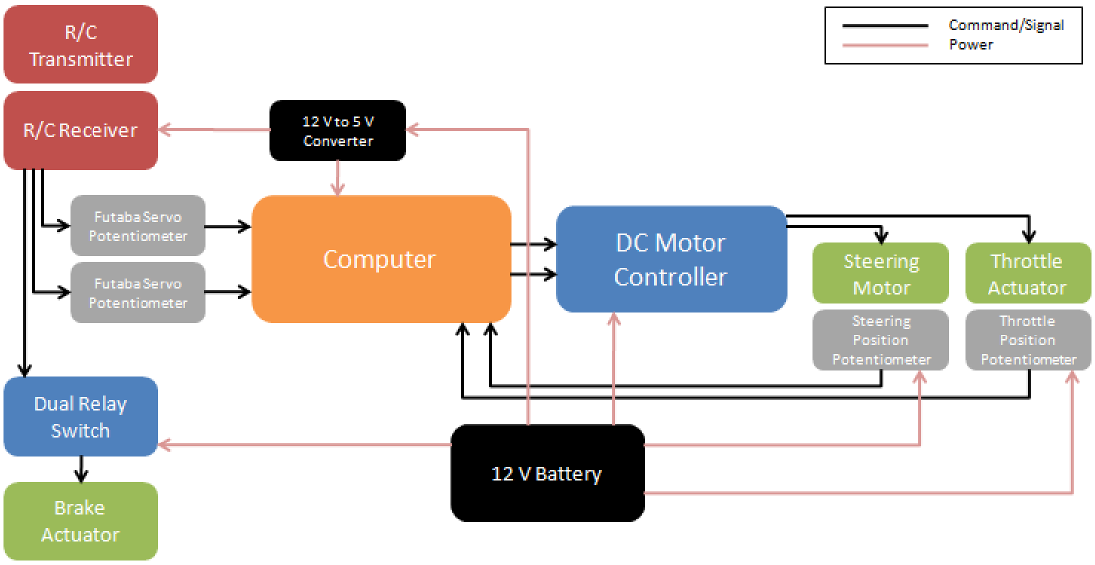

Figure 5.3: The Computer Control System Layout

Installing the computer system on the go-kart proved to be quite a delicate task. All the components had to be secured tightly and protected in case of collision, especially the Athena computer. Still, the go-kart had limited space for mounting, complicated by the desire to have all the components accessible for easy troubleshooting. With these objectives in mind, securing the components required careful planning and cautious work. The 80/20 steering frame was a convenient mounting base, but also obstructed possible mounting configurations. However, after hours of fastening and wiring, the vehicle was fully equipped (see Figure 5.4) and testing of the system could begin.

Figure 5.4: The Vehicle Equipped for Computer Control

5.2 Testing of the Computer Control System

Computer control testing began with the vehicle stationary on the ground and the engine off. Before the R/C transmitter was used, sine wave commands were generated by the computer to ensure that the actuation system was functioning properly. The actuators responded as they should, oscillating between their two command extremes. It is important to note that the steering shaft was not connected to the steering motor at this point. The connection between the coupler and torque limiter was left undone to prevent any undesirable effects if the steering motor failed to function as it should. When correct functioning of the actuation system was observed, the Simulink program was modified to respond to the R/C transmitter signal and the steering shaft was connected. Commands from the transmitter were recorded on the Athena and sent to a laptop computer with a crossover cable. Actuator feedback was recorded simultaneously so the system response could be displayed graphically on MATLAB plots. These plots are ideal for evaluating the performance of the closed-loop steering and throttle control and are good tools for predicting the performance of the vehicle when driven. Data was collected for a number of initial tests, and is presented below.

Data related to the performance of the steering and throttle control loops was collected and evaluated graphically. Figure 5.5 presents a plot of the throttle response, governed by the closed-loop control implemented by the Athena computer. This plot verifies the correct functioning of the control loop, as the actual position of the throttle pedal follows the commanded position from the R/C transmitter. The actual throttle control signal sent by the computer to the motor controller is given in Figure 5.6. As stated earlier, a signal of 2.5 V corresponds to the “middle position,” or signal that results in no action. The actual throttle position is presented along with the control command for reference.

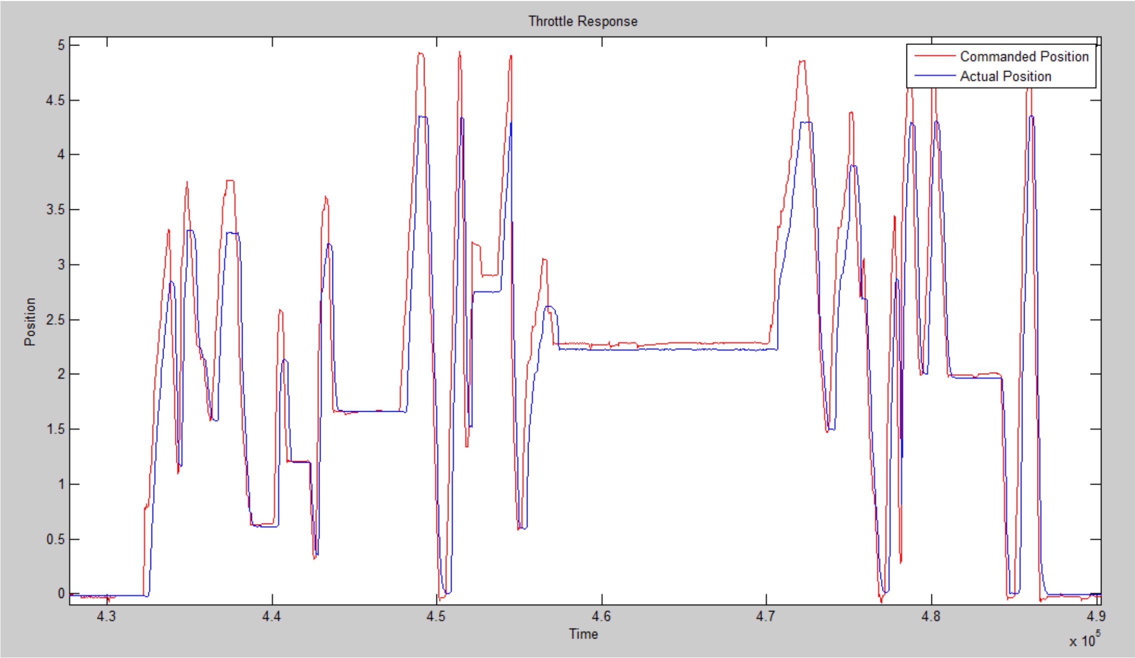

Figure 5.5: Throttle Tracking Response Plot

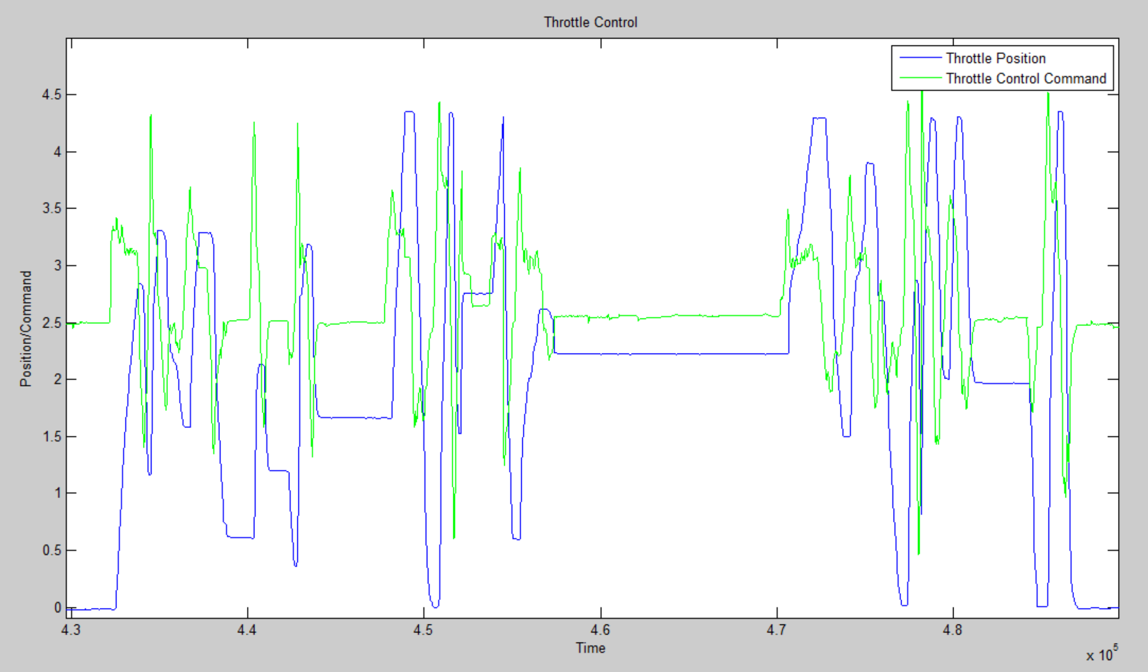

Figure 5.6: Throttle Control Command Plot

Notice that the control signal is proportional to the difference between the commanded position and the actual position, hence the name "proportional control." The greater the difference between the commanded position and actual position, the greater the control signal will deviate from the middle value of 2.5 V. Like the throttle plots, steering response and control plots are given in Figure 5.7 and Figure 5.8, respectively.

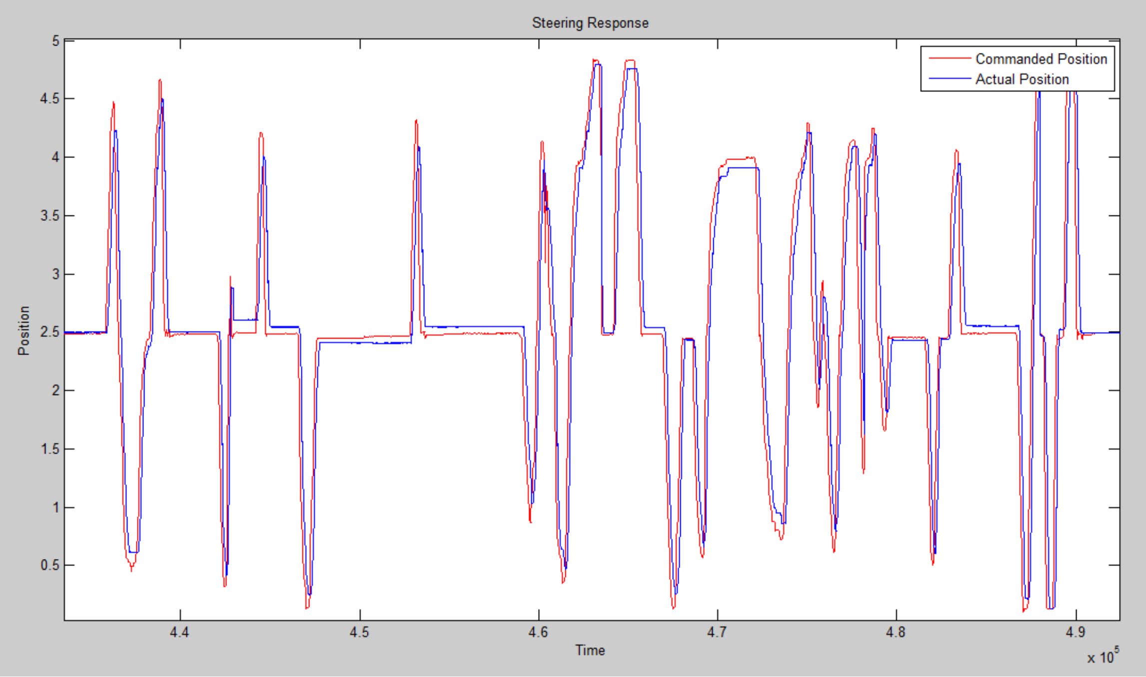

Figure 5.7: Steering Tracking Response Plot

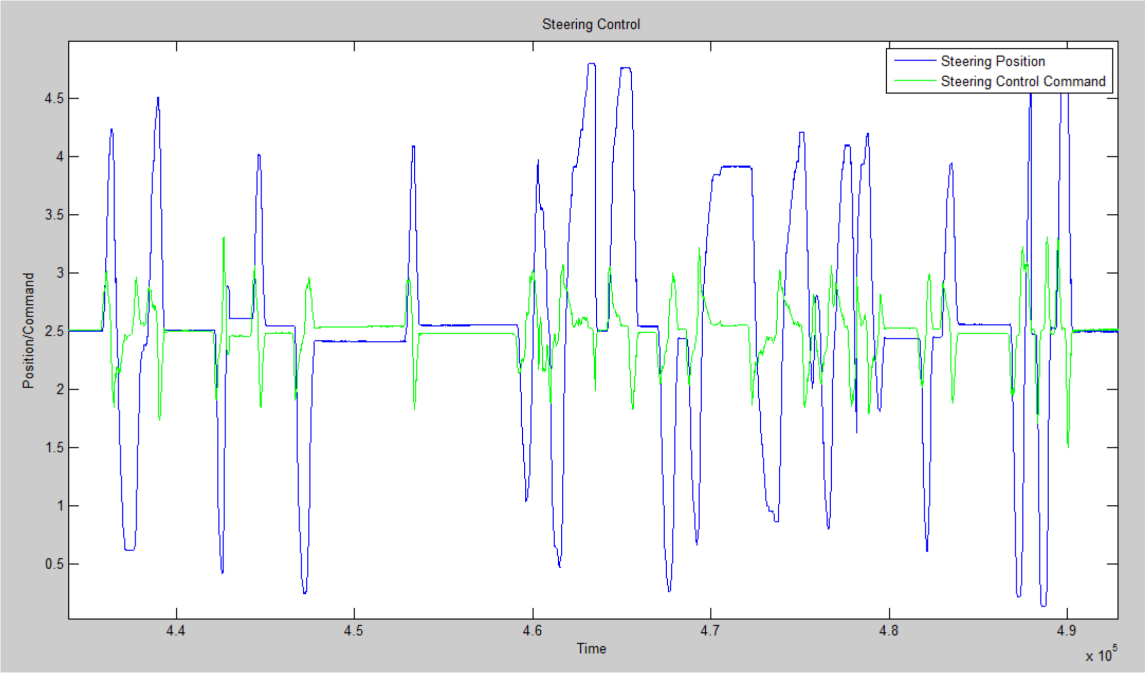

Figure 5.8: Steering Control Command Plot

The plots above validate the correct functioning of the closed-loop control, and provide confidence in the computer control of the vehicle. Once again, the go-kart was taken for another test drive, this time with complete success. The vehicle responded quickly to commands and the computer functioned properly, as did all other components of the system. Still, multiple aspects of the vehicle were identified for improvement.

5.3 Identification of Areas for Improvement

Throughout the computer control testing phase, two major areas for improvement were recognized. First, the Futaba servomotors contributed to a number of problems. The small servomotors draw all of their power from the R/C receiver, as they have no other power wires. Initially, the R/C receiver was only powered from the 5 V output on the

Roboteq AX2850 motor controller. This meant that the AX2850 also powered the two servomotors, an application for which it was not designed. The servos often drew too much current from the AX2850, and the motor controller would fail to accept the actuator control commands from the computer. Thus, the whole system failed. A simple solution was realized: power the R/C receiver from an external 5 V power supply. This power supply also powered the Athena computer, so it was available and already secured to the vehicle. Once this change was made, the motor controller ably commanded the actuators from the computer control signals.

The second area for improvement was the lack of a steady power source. Almost all of the components on the vehicle were powered by a single 12 V 18 AH lead-acid battery. It was soon discovered that this single battery lost charge quickly, and numerous problems resulted. Most noticeably and probably most importantly, the feedback potentiometers were wired to this battery, thus their signal voltage varied depending on the charge of the battery. This variation disrupted the control loops, as they relied on accurate feedback voltages to produce a control command. Surely, this was an issue that would have to be addressed in the next design revision.

Overall, the computer control of the vehicle proved to be successful. After much planning, construction, and troubleshooting, the closed-loop control performed as expected when implemented on the vehicle. The vehicle was driven once again, but this time using a system with much higher complexity. The added complexity allows the continuation of the go-kart development toward greater capabilities, and ultimately, long-distance teleoperation.

Chapter 6

Conclusion

The goal of this thesis was to develop a ground vehicle platform to be used for teleoperation. While teleoperation has not yet been accomplished, development of the ground vehicle platform can be considered a success. The off-road go-kart that was used for this project was transformed into a remotely-guided vehicle, complete with capable actuation and computer architecture to support wireless control. These results lay the groundwork for teleoperation to be achieved in the future.

Development of the vehicle did not go smoothly, and many lessons were learned in this process. Unforeseen obstacles were encountered that hindered progress, and even caused many design aspects of the vehicle to be iterated over and again. It was learned that even the best computer-aided drafting design of the go-kart and its actuation system cannot predict mechanical malfunctions. The steering setup failed twice, proving that optimal solutions can take time to develop. Computer control, while the most complex phase of the project, produced the most desirable results, proving that increasing complexity can increase performance when done correctly. Funds depleted and deadlines were pushed, yet all of these factors still contributed to the development of a vehicle that met its objectives. Because of the work that is described in this thesis, new possibilities can be explored in the field of unmanned ground vehicles, particularly teleoperated vehicles.

6.1 Future Work

Outlined below are some of the tasks that still need to be addressed on this project. Some tasks reflect improvements that should be made on the existing vehicle and some represent the next steps to be addressed on the way to teleoperation.

- Replace the Futaba servomotors with a microchip to count the pulse width of an incoming R/C signal
- Implement additional safety measures on the computer program
- Place emergency stops buttons around the outside of the vehicle for safety
- Route the brake signal through the computer, like the throttle and steering commands
- Power the feedback potentiometers off a regulated voltage supply so their feedback signal is more accurate
- Begin to develop a computer architecture to support wireless control of the vehicle
- Implement additional sensors like LIDAR on the vehicle

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APPENDIX

Products Purchased

Linear Actuators (2)
Firgelli Automation # FA-35-S-12-3”
Specifications: 3” stroke, 12 VDC, 35 lb, 2”/s
Price: $119.99 ea
http://www.firgelliauto.com/product_info.php?cPath=82&products_id=52

Servomotor (1)
Vantec # SSPS105S45
Specifications: Tonegawa Seiko, 27 ft-lb, +/-45 deg, 12 VDC, speed: 0.9 s/90 deg
Price: $524.95
http://www.vantec.com/ssps105.htm

Absolute Magnetic Kit Encoder
Digital (3)
US Digital # MAE3-P12-250-220-7
Specifications: 12-bit PWM output
Price: $50.90 ea
Analog (1)
US Digital # MAE3-A-250-220-7
Specifications: 10-bit analog output
Price: $43.90
http://www.usdigital.com/products/mae3/

Encoder Micro Connectors (4)
US Digital # CA-8703-1FT
Specifications: 3-pin connector, 26 AWG wires
Price: $5.00 ea
http://www.usdigital.com/products/connect/3pin-micro.shtml

Linear Actuator Mounting Brackets (2)
Firgelli Automation # MB1
Specifications: Clevis-pin triangular mount
Price: $18.00 ea
http://www.firgelliauto.com/product_info.php?cPath=70&products_id=54

Linear Actuator Wiring & Control Kit (2)
Firgelli Automation # EL-KIT
Specifications: external limit switches, 10A fuses, wiring
Price: $18.00 ea
http://www.firgelliauto.com/product_info.php?cPath=70&products_id=111

Torque Limiter (1)

RW-America # SK1/30/D/19.05/40/20-60/XX, XX = 30 deg re-engagement
Specifications: 40 N-m torque setting, zero backlash, 0.75” shaft, 30 deg re-engagement
Price: $292.04
http://www.rw-america.com/torque-limiters/torque-limiter-sk1_t.php

Timing Belt Pulleys (2)
McMaster-Carr # 6497K82
Specifications: 34 teeth, plain bore, 2.13” pitch diameter
Price: $48.80 ea
http://www.mcmaster.com/

Timing Belt (1)
McMaster-Carr # 7939K15
Specifications: Power Grip GT 5 mm, 450 mm outer circle, 90 teeth, 15 mm wide
Price: $16.60
http://www.mcmaster.com/

Misc. Parts
80/20 Inc.
Specifications: 10 Series aluminum profiles, drop-in T-nuts, corner brackets
Price: $760.90
http://www.8020.net/

Ignition Kill Switch (1)
Python Motor Sports # TGNfailkillswitch
Specifications: Loss of signal engine failsafe
Price: $38.95
http://www.pythonmotorsports.com/fg/offroad_parts/baja/Baja-5b-hopups.html

DuraTrax Micro Failsafe Units (3)
Tower Hobbies # LXHLV3
Specifications: Resettable failsafe signal
Price: $17.99 ea
http://www3.towerhobbies.com/cgi-bin/wti0001p?&P=9&I=LXHLV3

Geared Motor (1)
Robot Marketplace # AME-226-3003
Specifications: AM Equipment, 325 lb-in, 96 rpm, 12 VDC
Price: $67.99
http://www.robotmarketplace.com/products/AME-226-3003.html

Dual Relay Switch (1)
Robot Marketplace # 0-TD-RCE220
Specifications: Team Delta, relay load rating: 30 VDC, 12 A
Price: $37.99
http://www.robotmarketplace.com/products/0-TD-RCE220.html

Snapshots of the Vehicle in Action