PanaEVE Project Report

2011 Summer Quarter

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1 Executive summary

Carbon Dioxide emissions from transportation account for nearly a 3^{rd} of total emissions in the United States today which is second to only the process of electricity generation itself. With substantial Government interest in driving down, the carbon footprint of electricity generation by use of renewable sources, there is tremendous potential in replacing fossil fuels with electricity for the transportation sector. As we prepare for a greener tomorrow, transportation has to undergo sea changes be it in engineering, peripheral ecosystem or the overall psyche around cars. Electric vehicles have clearly shown promise to dial down emissions to zero. But unless the entire ecosystem surrounding electric transport changes, a battery powered vehicle still has limitations like charge life, low power density and high charging times.

Development for such large scale and ambitious projects as space travel, cancer treatment and in this case electric vehicles always has its "collateral damage". It leads to spinoffs of ideas into successful technologies that can be effectively used elsewhere. Aiming to target the ecosystem affected by research on EVs, PanaEVE project started in Stanford in Sumer 2010. With the use case scenario of 2020's Europe in mind, PanaEVE so far has built a 3 wheeled electric car for Europe's to be aging population in 2020. While the car incorporates some key features for effective use in 2020 like ease of parking, greater maneuverability, easier disabled entry and exit, it lacks a controller as of today. The goal of this summer effort of PanaEVE was to exhaustively look at different controllers for vehicle steering and to identify potential candidates for further exploration.

An electric vehicle typically has a drive-by-wire (X-by-wire) steering system. This system replaces the traditional mechanical control systems with electronic control systems using electromechanical actuators and human-machine interfaces such as pedal and steering feel emulators. Thus, in terms of number of components and space occupied, this is a huge bonus. The entire steering column replete with mechanical linkages like rack and pinion can now be replaced by a controller operated by driver and some intermediate electronics and sensors. Resulting savings in space, number of components and potentially cost can be huge. The reemergence of EVs has put even more emphasis on X-by-wire technology just because it is possible to have this technology at little marginal cost. An electronic control unit handles the transmission drivetrain; adding another module for steering is a low overhead.

This being said, there is considerable reluctance to pursue with this technology so far, one of the main reasons being passenger safety. Concerns over the integrity and fidelity of the steering control system including sensors feeding into the unit have made drive by wire take a back seat. Another significant factor militating against commercial deployment of this technology is the learning curve associated with driving in general and steering in particular. Direct mechanical feedback from the tires in a way that is now widely recognized as 'intuitive' is still one of the irrefutable advantages of having a conventional steering wheel installed in a car. Is there thus, a middle ground in using a drive by wire but using a (non-mechanical) steering wheel as a controller?

Numerous studies have established that a realistic 'haptic' feedback goes a long way in making steering intuitive. Prof. Chris Gerdes' lab at Stanford has working prototypes of a steering wheel coupled to motors that can generate resistive force depending on vehicle and road load conditions. A highly detailed model can quite effectively mimic the feel of an actual steering wheel. Answering the fundamental question whether a wheel is a 'better' controller than a navigational joystick, another study [12] showed that there was a significant advantage in driver tracking performance with the use of a steering wheel with force feedback. However, there are definite advantages for the joystick in evasive maneuvering situations. (It was also observed during the lane change event that the joystick controller required less work (smaller controller movements) from the driver.

Figure 1: Driving 2020: Semi-autonomous driving with assistive modules like platooning (shown above), lane assist, parking assist

To come back to the 2020 situation, it is not unreasonable to assume that some of autonomous driving technology ventures would be at a stage of implementation. University of California, Berkeley autonomous driving research has established 'platooning' as a viable option for highway decongestion and driver de-stress. Platooning is a 'module' of autonomous driving where the driver just has to plug into the module (or navigate the car into a freeway lane) and the platooning mode takes care of guiding the car through the lane until exit is reached. A less autonomous version of platooning is 'Lane Assist' wherein sensors can detect and warn the driver when lane boundaries are crossed by a car when it is not in a 'exit'/'lane change' mode. Thus from the point of view of carpooling, car-sharing, eco-driving it is assumed in our exploration that the notion of intuitiveness or ease of use of a controller needs to be re-examined. In other words, if driving in 2020 would end up needing very simple maneuvers like lane entering, exiting and parking (with the rest being handled by autonomous subsystems) then maybe the controller does not need to be overly sophisticated.

Based on some brainstorming exercises earlier in the project, we identified a few potential controllers that would be used for driving. Based on existing know how and potential of learning after a few weeks of exploration, we chose to study the joystick method of navigation. The underlying idea was to determine what features of the controller could be changed drastically – size, degrees of freedom, activated sense. In order to study how haptic feedback would affect driving experience, CHAI3D was chosen as the development platform for the simulation platform. To establish a simulation framework on CHAI3D on which future efforts can build off, we created a 'lane assist' simulation wherein the virtual car would be driven inside a lane and haptic interaction would be dictated by the car offset from the center of the lane.

After evaluating some basic questions on driver comfort such as one handed vs. two handed control, explorations pointed toward some other subtle features such as number of degrees of freedom controlled at a time, controller movement and control feedback algorithms. This report comprehensively describes findings from prototyping efforts summer 2011 and discusses future options.

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2.4 Glossary

AirPix: is an intuitive device that uses compressed air to safely create a refreshable, tactile "image" initially designed to help blind driver "view" the road, by Robotics & Mechanisms Lab at Virginia Tech.

Arduino: is an open-source single-board microcontroller, descendant of the open-source Wiring platform, designed to make the process of using electronics in multidisciplinary projects more accessible.

Aligning moment of the tire: is a function of the steering geometry, particularly caster and kingpin angles, and the manner in which the tire deforms to generate lateral forces. The effective lateral force does not act directly at the center of the contact patch. Rather, it acts at a distance known as the tire pneumatic trail, which induces a moment, known as self-aligning moment.

Bounding box: Limits of displacement of a controller along all degrees of freedom

CHAI 3D: is an open source set of C++ libraries for computer haptics, visualization and interactive real-time simulation. CHAI 3D supports several commercially-available three-, six- and seven-degree-of-freedom haptic devices, and makes it simple to support new custom force feedback devices.

Cursor: A virtual image of haptic device controlled by a user inside the CHAI3D simulation. This will also represent the car in our prototype

CyberForce: is the World's first "desktop" whole-hand and arm force feedback device - a force feedback armature that not only conveys realistic grounded forces to the hand and arm but also provides six-degree-of-freedom positional tracking that accurately measures translation and rotation of the hand in three dimensions.

Dead man's switch : is a switch that is automatically operated in case the human operator becomes incapacitated, such as through death or loss of consciousness.

Degrees of freedom: Number of independent directions/configurations in which a device can move or be moved

Drive-by-wire: DbW/ by-wire/x-by-wire technology in the automotive industry replaces the traditional mechanical control systems with electronic control systems using electromechanical actuators and human-machine interfaces such as pedal and steering feel emulators. Hence, the traditional components such as the steering column, intermediate shafts, pumps, hoses, belts, coolers and vacuum servos and master cylinders are eliminated from the vehicle. Examples include electronic throttle control and brake-by-wire.

Envelope Control: is an integrated control strategy, also known as carefree handling, use available actuators to prevent an aircraft from entering a state or control regions outside of the safe flight regime; similarly for vehicles, envelope control -- steering controller would engage and assist the driver to stay within the boundary.

ESC (Electronic stability control): is a computerized technology that improves safety of a vehicle's stability by detecting and minimizing skids

E-stop: is Emergency stop.

Falcon: See Novint Falcon

GM'S Onstar: OnStar Corporation is a subsidiary of General Motors that provides subscription-based communications, in-vehicle security, hands free calling, turn-by-turn navigation, and remote diagnostics systems throughout the United States, Canada and China.

Haptic Device: Usually a multi-degree of freedom device that can detect self position inside a bounding box and can generate forces along those degrees of freedom

HMI: Human Machine Interface

HVAC (Heating, Ventilation, and Air Conditioning): refers to technology of indoor or automotive environmental comfort.

iDrive: is a computer system which is used to control most secondary vehicle systems in many current BMW cars. iDrive's user interface consists of a LCD panel mounted in the dashboard and a controller knob mounted on the center console.

IMU(Inertial measurement unit): is an electronic device that measures and reports on a craft's velocity, orientation, and gravitational forces, using a combination of accelerometers and gyroscopes.

Lane: A set of 3 parallel lines inside the world. The two outer lines represent the lane boundaries and the middle line represents set of midpoints of the two outer lines.

Neuroergonomics: is the application of neuroscience to ergonomics, and can be defined as the study of brain and behavior at work.

Novint Falcon: A 3DOF haptic device that has been used in this project as a driving controller

PanaEVE: is a Stanford University research group in the department of Mechanical Engineering generously funded by Panasonic with a project mission to understand the trends of Emerging Vehicle Elements (EVE) and to develop prototypes to further satisfy the needs of the 2020 automobile user.

Platoon: is to group vehicles so as to decrease the distances between cars using electronic, and possibly mechanical, coupling.

Power-assisted Steering: is automotive steering where engineer power amplifies the torque applied to the steering wheel.

Rack and Pinion System: is a type of linear actuator that comprises a pair of gears which convert rotational motion into linear motion.

Sensory substitution: means to transform the characteristics of one sensory modality into stimuli of another sensory modality.

SoftHaptics: The essence of SoftHaptic interfaces is to use visual cues and/or tonal cues to interpret sensed data feedback from remote robotic systems with which the operator can construct the same mental image of what happens there as using haptic interface devices.

Steer-by-wire: is to completely do away with as many mechanical components (steering shaft, column, gear reduction mechanism, etc.) as possible.

Teleoperation: means to operate a vehicle or a system over a distance.

Vehicle-to-Infrastructure (V2I): is the wireless exchange of critical safety and operational data between vehicles and highway infrastructure.

Vehicle-to-Vehicle (V2V): is an automobile technology designed to allow automobiles to "talk" to each other.

World: Simulation environment containing road geometry and an image of the haptic device as a cursor

X1 Vehicle: is a second-generation drive-by-wire vehicle developed by DDL Lab at Stanford University. More information can be retrieved from: https://ddl.stanford.edu/x1.

3 Design Requirements

These requirements start out as being universally applicable to most steer by wire controllers (apart from a steering wheel) but then go on to specifically describe the key features necessary for a joystick controller.

3.1 Hardware

Functional requirements

Requirements	Metrics	Rationale
Controller should be able to replicate a steering controller for navigating a vehicle on a road inside a simulation	It should have at the minimum, functions for moving in 4 directions and changing speed of the car	These functions are bare minimum in order for the controller to be practically usable
Controller should have multiple degrees of freedom	It should have at least 2 degrees (and more)	More degrees of freedom provide for greater functionality.
The different degrees of freedom should be user customizable	Prototype should be easily movable along certain preset degrees of freedom and restrained along others	More degrees of freedom do not necessarily imply that a controller would be more intuitive or suitable for driving. Hence control over excess degrees of freedom becomes essential
Prototype should have a haptic feedback associated with position of the virtual car with reference to the virtual environment	Haptic force should direct the car toward the most stable (lowest energy) position in the current driving configuration.	Haptic feedback has been proved to be effective in assisting the driver in drive by wire situations
Controller movement in each direction should be substantial	The overall travel in each direction should be at least 24 inches measured along a linear route	Small controller movements imply heightened sensitivity which can be detrimental to driving experience
In the absence of driver input, the controller should be able to steer the vehicle on course	If in lane assist mode, the controller should straighten the vehicle automatically in case user response is missing	This is a key factor in the safety of x-by-wire. Mechanical steering wheel has this built in partially because of the toe-in and camber present in the wheels.

Functional Opportunities

- Other degrees of freedom in the controller can be used to perform other functions (navigational or vehicle environment control)
- Grasping can be an extra degree of freedom
- Controller can have haptic feedback based on tire conditions instead of car position conditions. In this case, it would be more similar to the conventional steer by wire controllers. This situation has been abundantly studied in literature and hence has been skipped over in our study
- The controller can be collapsible instead of being completely detachable. This can ensure that entry and exit are smooth for the driver.

Physical requirements

Requirements	Metrics	Rationale
Controller should be a form factor that can fit in the space inside a mini-car	It should fit the PanaEVE car with reasonable entry/exit space and leg room	It is reasonable to assume that controller would be inside the cae
Controller should be modular/portable	Right and left handed people should be able to place the controller in a position that is most suited for them	Unlike a steering wheel, a one handed controller would need to be flexible in its location for ease of usage.
Controller should be platform/car independent	IT should be of a plug and play variety that can be used essentially like a USB drive is today	In times of car sharing, a universal controller has the potential to save a lot of incompatibility hassles
Controller should be small in overall size	It should fit into a standard shopping bag	In times of car pooling and car sharing, this can enable people to use their own controller for driving eliminating any health risk associated with contagions
Controller envelope should be fixed	Travel in different directions should be pre-set to a value of around 12 inches	A variable travel can give inconsistent driving feel
Controller should be light weight	Should not weigh more than 5 pounds	Energy efficient driving is directly correlated with weight of the car. Thus it is imperative that the controller should not be unnaturally heavy. In fact, the steering module together should have some predetermined cap on weight

Physical opportunities:

- Controllers can be 'retrofit' according to the taste of the drivers. Since the primary control system would be x-by-wire, a central component connected to any number of peripheral controllers would still do the job
- Controllers can be collapsible, movable, adjustable inside the car to allow reconfiguration of space.

User Requirements

Requirements	Metrics	Rationale
User should be able to easily move the controller to steer virtual car	Stiction on the joystick should not exceed 0.25 lbs	Joystick is crucial for evasive maneuvering. A stuck joystick can severely compromise this aspect
Basic navigation controls should be intuitive	User should be able to figure out navigation controls without any instructions before the test	Comfort with the controller is fundamental to driving experience and safety
Controller should be user customizable	Sensitivity of the joystick control should be user dependent, so should be the choice of degrees of freedom	Based on tests conducted in this Summer effort, users prefer different levels of sensitivity when using a joystick for steering
Controller should be mobile	Right and left handed people should be able to place the controller in a position that is most suited for them	Unlike a steering wheel operated with both hands, a one handed controller would need to be flexible in its location for ease of usage.
It should be comfortable to drive the car	Extended period of driving should not manifest itself in the form of wristaches, or painful forearms	Comfort is crucial for driving safety and pleasure
Driver should feel safe using the controller	Driver should not express lack of confidence after the first trial run on the driving simulator	The first trial brings with it the steepest learning curve ("Who moved my cheese' phenomenon)

User opportunities:

- Controller can have multiple 'grips' or ways in which users would touch and operate them
- Controller can have one handed or two handed grasping depending on preference

3.2 Software

Software Requirements

Requirements	Metrics	Rationale
Software should be able to emulate the basic driving scenario	It should have 2 lanes and a dot representing the car as a "really bare bones (RBB)" simulation structure	This minimalist controller can still give useful insights about driving feel
Simulation should have camera movement closely mimicking first person driving situation	At a given instant, only that part of the horizon that is being faced should be visible on the screen	To give a closer to life feel inside the environment
Simulation should have straight as well as curved roads	For every 'x' units of straight line, the map should have at least 'x/2' length of curves.	Controllability is put to the test only on curved roads. Also, this is more representative of real life
Simulation should be able to change speed based on controller based input function	Speed should be proportional to travel along the 'speed degree of freedom'	This way, throttle and braking can be integrated into the handheld controller itself
Software should predict instantaneous force for haptic feedback associated with position of the virtual car with reference to the virtual environment	Predicted force should be a function of deviation of car from the center of the potential energy well inside the simulation	This exercise aims at testing 'position-based haptic feedback'
Prototype should be able to map directions of controller motion to a virtual simulation	The RBB version should have functions to 'strafe' in left –right directions and to 'glide' in forward – backward directions	This is an effective scheme to model the haptic feedback based lane assist during freeway driving
Software should be hardware independent	Simulation environment should be able to interface with other generic steering controllers apart from Novint Falcon identified for this project	This is for ease and comprehensiveness of user testing
Gains for proportional, differential and integral components of the control system should not cause instability of system	As a rigid metric, poles of the system should be to the left of 0, a more pragmatic metric is that system should not lose stability after 10 consecutive trial runs	System instability is arguably one of the gravest cause of accidents

Software Opportunities

- The simulator could be built in the form of modules and future iterations could call on these modules to build a more sophisticated simulator
- There is potential to sync up CHAI3D with Arduino. This would enable testing non standard haptic devices on the CHAI3D platform
- Mapping of controller deviation from Neutral to speed of the car can be non-linear.

Prototype Constraints/Limitations

- Prototype for the controller would be a standard off-the-shelf haptic device since there is significant documentation for its usage and a considerable potential for future crossover into a more graphically intensive simulation platform
- Maximum travel along unrestrained degrees of freedom would be limited by the Novint Falcon, a standard haptic device used in this exercise.
- The driving simulator has to be coded in CHAI3D (till a better interface to talk to standard off the shelf haptic devices is developed)
- Other constraints in software were imposed solely based on the limited documentation of CHAI3D. An experience CHAI3D user should have no difficulty in setting up complex simulators on this platform

4 Design Development

4.1 Needfinding and Benchmarking

Given the background of PanaEVE project, the Team aims to design a steering system for the designed Steer-by-Wire automobile to satisfy the need of 2020 European old users. Figure 2shows PanaEVE car based on which we design the steering system.

Figure 2: PanaEVE Emerging Vehicle designed for 2020 European old users

To investigate into this project, the Team started with understanding steering history of automobiles, which evolved from mechanical control system to hydraulic control system and finally is reaching by wire control system. The advantages and disadvantages comparing traditional mechanical control system with steer-by-wire system are listed in **Error! Reference source not found.**.

The sense for driving mainly includes[1] Vision, which is the most important element, Haptic Force Feedback, which conveys the frequency and magnitude of the torque/force caused by the interaction of car with the environment, and Vestibular channels of inner ear, which conveys the feeling of balance while driving the car. As can be observed from the comparison, as one of the most important features for driving sense, Haptic Steering is needed for Steer-by-Wire automobiles, to convey noise, vibration and harshness (NVH)[2] from the road to the driver.

Table 1 Advantages and Disadvantages comparing Mechanical Control with Steer-by-Wire systems

	Mechanical Control	Steer-by-Wire
Safety	More reliable and repairable.	Safety can be improved by providing computer controlled intervention of vehicle controls with systems such as ESC, adaptive cruise control and Lane Assist Systems.
Cost	Cheap	Expensive. The extra costs stem from greater complexity, development costs and the redundant elements needed to make the system safe.
Ergonomics	Hard to customize	Improved by the amount of force and range of movement required by the driver and by greater flexibility in the location of controls.
Steering Feeling	Natural	Has to involve haptic steering feedback to enhance driving experience.

Before looking into haptic steering, the Team did some researches into the background of the project, understanding the design requirements by learning about the initial users and road situation in Europe, which is mainly through interviews. Interview details can be found in 1.1.2.

4.1.1 Exploring Haptic Steering

The definition of Haptics is "sense of touch". Haptics has been widely applied in various areas of study including enhancing driving experience for Steer-by-wire automobiles. Haptic Steering is called by the necessity for the driver to feel a simulated reaction torque related to tire/road interactions for Steer-by-wire vehicles, aiming at improving driving comfort, performance, and safety. There are different types of tactile display including Vibration Feedback; Contact Location, Slip, and Shear Display; Local Shape; Temperature [3]. Different ways of haptic display stimulate the early brainstorming of controller.

Based on existing research works in Haptic Steering, the Team found out that most haptic steering systems in these researches utilize hand-wheel or joystick, with force/torque feedback to simulate traditional mechanical control system.

Virtual Reality

There are also haptic researches combined with Virtual Reality, such as Haptic Workstation™ developed by Immersion Corporation, Airborne Ultrasound Tactile Display[4], in which a hologram projector uses an ultrasound phenomenon called acoustic radiation pressure to create a pressure sensation on a user's hands, which are tracked with two Nintendo Wiimotes (controllers for Nintendo's Wii console), as shown in Figure 3.

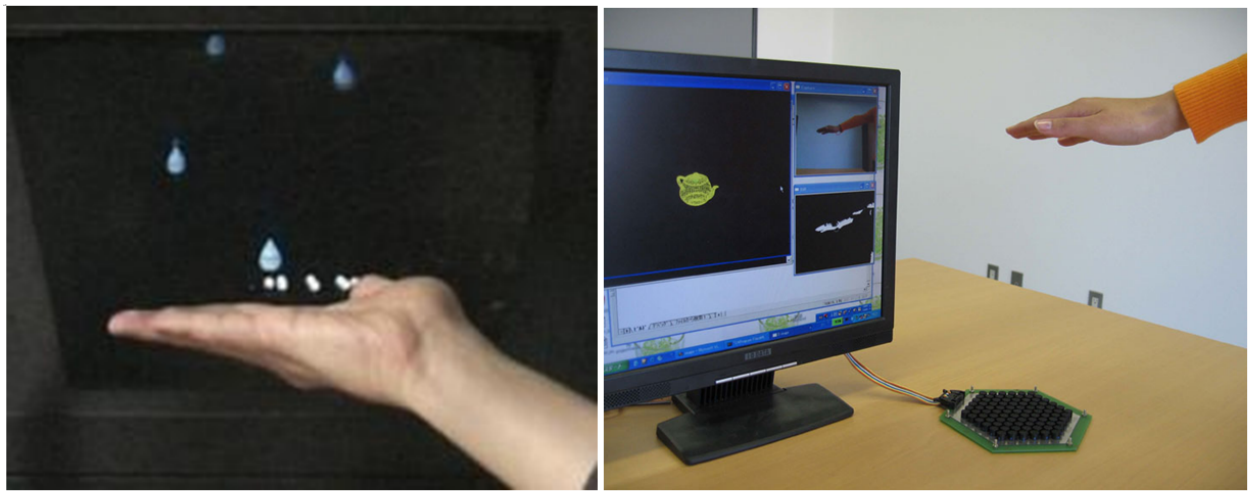

Figure 3: Airborne Ultrasound Tactile Display take use of acoustic radiation pressure to create a pressure sensation on a user's hands

Sensory Substitution

Another branch of researches in haptics is sensory substitution, which is mainly studied to help handicapped people by restoring their ability to perceive a certain defective sensory modality by using sensory information from a functioning sensory modality. Other potential applications are developed, such as Tactile Vision Sensory Substitution (TVSS), with the help of technical developments such as miniaturization and electrical stimulation [5]. Audiovisual feedback has been proved essential to the usability of an interface. Some authors have even considered that traditional haptic feedback (mainly force/torque) can be replaced by the right combination of sound and visuals [6].A simple idea could be to let the loudness of the tone indicate the magnitude of the force. Another concept of "SoftHaptic Interface" is brought up in several researches [7] to avoid the unavailability and incompatibility of haptic interface devices for teleoperation of robots. It's pointed out that because there are no direct force interactions (no energy-coupling) between the operator and the remote robot, there is no operator-induced instability.

In summary of the research work into Virtual Reality and Sensory Substitution, the Team has found great potential of these technologies to be applied in the steering controller design, in addition to the traditional application of force/torque feedback of Haptic Steering. However, limited to the time and resources the Team had, the main focus was on the traditional way to design the steering system. In the future, Virtual Reality and Sensory Substitution can be taken into consideration for the design of Haptic Steering system.

Haptic Steering

Before looking into Haptic Steering, it's necessary to understand the steering system. The traditional steering system is characterized by two distinct on-center (vehicle traveling nearly straight) and off-center properties. On-center handling quality has been identified as a function of three characteristics: steering activity, steering "feel," and vehicle response. The steering activity is composed of hand-wheel angle, rate, and torque activities. The "feel" is made of steering friction, torque dead band, and steering stiffness. The vehicle response is made of response dead band, yaw rate response, and response time lag. A vehicle is considered to have good on-center handling if it requires minimal correction and instructs the driver how much correction to apply and then proceeds to apply the driver's command accurately. Meanwhile, the off-center measures are typically twofold: the torque magnitude felt by the driver manifested by torque stiffness and dynamic response manifested by time delay between hand-wheel input and vehicle responses. More about steering feel can be found in [8], [9].

The purpose of Haptic Steering is to provide with force/torque through steering wheel and throttle, especially for detecting sudden changes in tire/road friction as well as anticipating control responses for roadway disturbances and wind gusts[9]. Some paper discussed about various metrics that are used to define steering feel[10] with hand-wheel, in which it's found that subjects focused on the steady state force that they applied to the wheel rather than the steady state torque, and on the angle that they turned the wheel rather than the displacement of their hands. It seems that subjects used the forces in their muscles and the angles at the joints of their hands and arms to position the steering wheels. It further discussed about the relationship of the rate of growth in the perception of steady state steering-wheel force and steady state steering-wheel angle, which can alter driving experience. As for the user persona, it's pointed out that driving safety, particularly which of older drivers with cognitive impairments, is a fruitful application domain for neuroergonomics[11]. Other useful references that the Team took use of in the brainstorming stage are [12] and [13]. These works helped define design requirements and can also be used to evaluate the prototypes we developed.

4.1.2 Exploring Steering Controllers

Teleoperation Controllers

Traditional teleoperation controllers are constituted by adhoc controls such as joysticks or buttons, complemented with visual feedback obtained from robot-mounted cameras. A novel teleoperation controller mentioned above is Haptic Workstation (shown in Figure 4) with 6D haptic interfaces in combination with Virtual Reality techniques with wearable devices, enabling realistic 3D virtual objects, haptic force-feedback and free arm gestures. The main disadvantage is that the driver cannot take hands away from the device because of the restriction of gloves [6]. SoftHaptics can also be considered as teleoperation controllers. For teleoperation, no mechanical connections are involved, which causes the need of haptic feedback for this kind of controllers.

Figure 4: Haptic Workstation: a virtual prototyping tool incorporating CyberForce and feedback systems

Direct Controllers

Direct controllers are mainly traditional steering controller systems. The team did some researches into various control systems in the history of automobiles, ships, airplanes and other machines. These resources helped with brainstorming in the later stage.

1. Hand-wheel

Traditional hand-wheel controller is a typical example of direct controller that has also been widely studied to be used for haptic steering systems. Generally, steering with hand-wheel is more preferable than joystick. Detailed description and experimental results of comparing the performance of hand-wheel and joystick can be found in [14].

As shown in Figure 5: Joysticks in cars: Mercedes Benz SCL 600 (A concept car/myth), the main concept of Mercedes Benz SCL600 is the replacement of a steering wheel with a joystick. Joystick is designed to replace hand-wheel in order to avoid driving pains and should sprains. The purpose is to make driving experience easier and better while eliminating the problem of pains. However, since this car has never entered market, no sufficient data shows whether joysticks work better than traditional hand-wheel.

Figure 5: Joysticks in cars: Mercedes Benz SCL 600 (A concept car/myth)

In Figure 6: Joysticks in aircrafts: Yoke (left) and Center stick (right)., joysticks are the principal control in the cockpit of many civilian and military aircraft, either as a center stick or side-stick. They often have supplementary switches on them to control other aspects of the aircraft's flight.

Figure 6: Joysticks in aircrafts: Yoke (left) and Center stick (right).

2. Two- handed handle

Two-handled handle controllers are widely used in bikes, motorcycles, auto rickshaws, ATVs, etc., as shown in Figure 7: Two-handled handle: Auto rickshaws (top) and ATVs (bottom).

Figure 7: Two-handled handle: Auto rickshaws (top) and ATVs (bottom)

3. Horizontal steering wheel

The Drive-Master horizontal steering system is customized to meet the needs of those with high-level spinal cord injuries and all others who experience limited arm strength and range of motion[15]. Figure 8: Drive-Master horizontal steering system shows how the horizontal steering wheel controller works: on the base of a hand-wheel, a supporting stick holder is mounted to satisfy easy use for handicapped people.

Figure 8: Drive-Master horizontal steering system

Features include:

- Eliminates the arm-lifting motion normally needed to steer.
- Fully adjustable in all planes.
- Telescopes for maximum driver adjustment and comfort.
- Can be installed on any tilt or non-tilt steering column.
- Does not interfere with the O.E.M. collapsible feature built into the steering column of every vehicle.
- Optional interchangeable system allows conventional steering as well.
- Must be used with powered gear selector, electric directional signal, remote ignition, and remote wipers, if equipped

4. Steering with feet

Foot steering systems completely free the use of hands. Initially designed for customers without arms, as shown in Figure 9: A Drive-Master customer's loafer attached with steering pin to the foot steering wheel, Drive-Master has designed this steering system with steering pin attached to the foot steering wheel. Another example shown in Figure 10: Trikebuggy foot steering kit9 is a TrikeBuggy Intuitive Foot Steering System that allows hands-free operation of the steering of glider with feet during the flight[16].

Figure 9: A Drive-Master customer's loafer attached with steering pin to the foot steering wheel [17]

Figure 10: Trikebuggy foot steering kit

5. “Point and shoot” -Turret steering

Figure 11: Gun/Turret Station built with Clone Troopers Battle Pack

Figure 11: Gun/Turret Station built with Clone Troopers Battle Pack is a mini model of turret station built with Clone Troopers Battle Pack. This figure inspired the Team: Can the steering controller be a small turret itself?

6. Tracking pad steering

Figure 12: GM EV-N Xiao (Laugh) concept retractable user interface

Tracking pad Steering is an idea to incorporate smart phone with steering system. Typical example is GM's EN-V, short for Electric Networked Vehicle, which is a vision of the future of urban personal mobility, as shown in Figure 12: GM EV-N Xiao (Laugh) concept retractable user interface.

7. Tiller Steering

Tiller Steering is traditionally used in ship steering as shown in Figure 13: Ship tiller steering. Applications in other vehicles are shown in Figure 13: Ship tiller steering. Steering with a tiller needs less movement than a steering wheel and some people find the horizontal grip easier to use. Holding the tiller can also give you more stability [18].

Figure 13: Ship tiller steering

Figure 14: Tiller Steering

4.1.3 Interviews

Avinash Balachandran

Who: A Master student in DDL lab at Stanford University

Date: 7/7/2011 - 11:00am & 7/12/2011 - 6:00pm

Project Title: FFB (Force Feedback) project

Overview: The project is to introduce haptic force feedback to steering wheel in Steer-by-wire automobile for X1 vehicle, so as to enhance performance and safety during driving. It's an application of Envelope Control. Avinash has built a prototype of steering system at this stage.

Feature: to limit the wheel's turning angle to, for instance, 180 degrees, with the design of physical boundary in the steering system to enhance safety. (Usually the driver turn the wheel many rounds, and can't turn back as soon as possible)

Purpose:

- To study tire/road interaction, mainly aligning moment.
- To design the control system, electronic parts, build the prototype and test it.
- The wheel is adjustable (not fixed in one position) so that can fit for different users.
- To involve human driver in the loop of feedback control. "Human-in-the-loop"
- To implement the system in X1 and drive to test the prototype

Useful simulation software: dspace Automotive Simulation Models

Key Learnings:

- There is no delay for mechanical built cars, but there is time delay of command for steer-by-wire.
- Motor: the motor has its own torque when it's not driven. Choose a suitable motor for the car.
- Haptic Steering doesn't include haptic interface for communication, entertainment.
- Joystick might be an interesting direction to explore.
- Idea Avinash suggested for PanaEVE: Make the steering wheel storable, modular, so that it won't take much space in the car
- A proper range of torque feedback for haptic steering: ~8Nm to ~14Nm
- Reasonable time latency: < 10 millisecond
- No commercial use of Haptic Steering exists, since all commercial cars are traditional ones. The steer-by-wire history can be tracked back to ~5 years ago.

Michael Helms

Who: An experienced engineer & Master student at CDR, Stanford University

Date: 7/26/2011- 6:00pm

Key Learnings:

- Is haptic feedback even necessary? -- To design a steering system in a bigger scenario.
- To design the steering system to make driving simple.
- 9 senses to explore: **sight**, hearing, smell, taste, **touch**, thermoception, nociception (physiological pain), equilibrioception (**the vestibular sense**), proprioception (the kinesthetic sense). Bolded are key elements for driving.
- Human Information Process: Input → process → output
- Keep in mind of driver behavior of 40+ years old, European. Possible features: Alcoholic? Sleepy?
- How to make it ATM-simple? Intuitive to use?
- What's the higher, lower priority of the system? What do we want most out of the system?
- Involve positive feedback, get rid of negative feedback
- Is the system adaptive to different kind of users?
- Does the system incorporate different ways to use the controller?
- Is it a forgiving system? (It can behave like a coach to keep the driving from making mistakes?)

Sven Beiker

Who: the Executive Director of the Center for Automotive Research at Stanford – CARS

Date: 7/28/2011 – 1:30pm

Key Learnings:

Q: How do you think EV andSteer-by-Wire can be in 10 to 15 years?

- prefer the conventional automobile, which would probably still take the priority
- there's lower expectation than people think
- EV's advantage: More quite, simple to use as for mechanism/powertrain.
- "like" and "buy" are different

Q: What's the background of automobile manufacturing and researches in Europe?

- In Europe, mobility providers are exploring new grounds in automotive researches.
- Car-sharing is the trend, decided by the traffic in Europe.
- Less attachment is the trend, since users won't care about what the car is. (But will be stylish?)
- An example of electric car in Europe: "think" EV (http://www.thinkev.com/)

Q: What do you think of the potential market for autonomous cars?

- No autonomous in 15 years for small cars.
- Autonomous is difficult in city driving. (On the other hand, it's useful for parking/emergency/pedestrian detection/stop and go assistance etc.)

Q: How do you think of the trend of automobiles – getting connected?

- Your lifestyle is extended (phone call, working, eating...)
- Cars are talking to each other (better traffic management, collision avoidance, ride sharing possibilities, safety)
- People are using instant messaging (texts, twitter, status updates to communicate more than e-mails), this in combination with reliable speech to text may make it possible for people to use the feature to communicate /dictate messages while in the car (wengmotors.com)
- "Driving +": Driving will not change too much, but the "+" will change a lot.
- The combination of information technology with car is a little tricky, since car companies can stay relatively the same for 50 years, but the IT market can change a lot in several years.

Q: What do you think of safety issues for cars like PanaEVE?

- Small cars are not safe! (compared to a truck)

Q: What do you think of space-occupied issues for cars like PanaEVE?

- Cars can be designed highly maneuverable.
    - To "push" your car instead of "drive".
    - To go shopping with your car'

Q: About Steering system

- For the last 100 years, other steering controllers haven't been worked out better than wheels
- Steer-by-wire is the trend? –At least it's not legal now.
- **Challenges**: Electronics fail fatally, but mechanical system can be repaired.
- **Benefits**:
    - Modular (the controller can be put anywhere in the car)
    - The control systems are easy to be applied (already existing today)
    - In a car crash, there won't be a column in front of the driver.
    - Saves weight and space.

4.1.4 Non-steering Haptic Applications in Automobiles

Other haptics-based features such as LCD touch screen, Console/Wheel Control Switch have also been widely explored with the trend of incorporating intelligent system into automobiles. The following manufacturers are launchers for the haptic applications.

Hyundai has developed iDrive-type HMI controller including haptic feedback dubbed 'Intelligent Haptic System'. The Intelligent Haptic System consists of [19]:

- The Lumino Haptic Console Switch, a driver seat's main controller with haptic and Lumino functions.
- The Haptic Steering Wheel Switch, a haptic function switch on the steering wheel.
- The Haptic Touch Screen, an LCD touch screen with dashboard switches on it.

Lexus Hybrids has developed "Remote Touch" Merge Mouse, Monitor and Windshield to enhance haptic feedback for user interface [20].

Mercedes COMAND's 8-way joystick controller enables virtual control over all features in the car, including the navigation system [21]. Figure 15: Mercedes' COMAND system controlled via the single-knob iDrive-style joystick located in the center consoleshows Mercedes' COMAND system interface.

Figure 15: Mercedes' COMAND system controlled via the single-knob iDrive-style joystick located in the center console

Other non-steering haptic features include KIA touch panel & haptic steering wheel switch [22] and Jaguar's Multi-media [23].

4.2 Brainstorming

After Needfinding and Benchmarking, the Team started brainstorming with two questions: What kind of haptic information is needed to be conveyed to driver? What kind of controller do we choose to apply to fit PanaEVE background?

Figure 16 shows the trend of automobile technologies from current anti-lock braking system to possibly fully autonomous automobile systems, based on the benchmarking knowledge the Team gathered. As can be observed from this figure, by the time steer-by-wire vehicle is in market, most car-assistant systems can be assumed available. It triggered the Team to think about how to choose and combine these systems for our steering system, and how to take advantage of them to enhance the function of haptic steering.

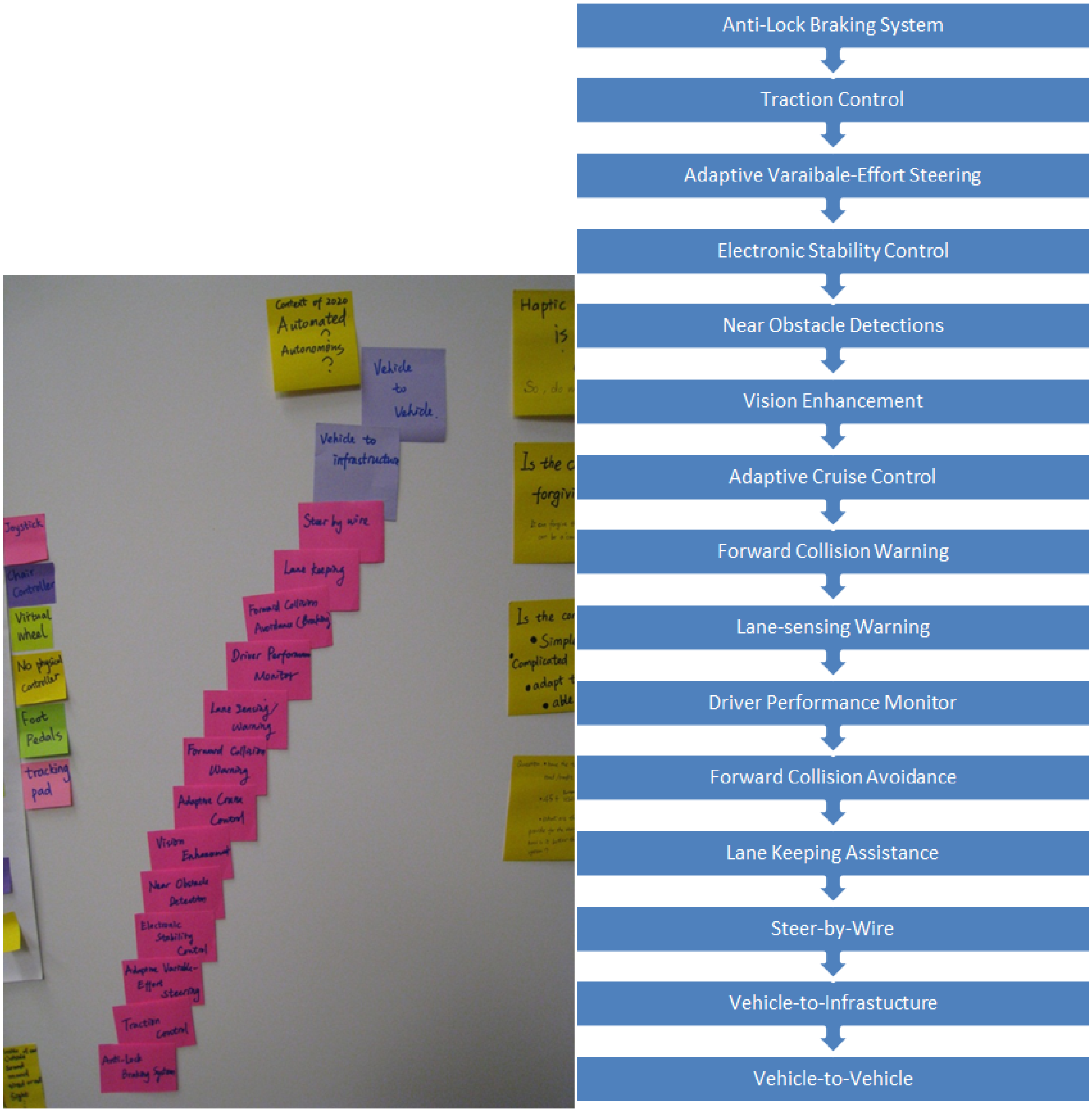

Figure 16: The trend of Automobile Technologies shows the context of Steer-by-Wire vehicles

Type of controllers

The team brainstormed about what kind of controllers could be used for PanaEVE car, ideas including steering hand-wheel, joystick(s), bike-handle, foot pedal, etc. Some interesting ideas are elaborated here for future reference:

- Armrest of chair as the controller
    - The feedback path is the same as control path: armrest
    - The feedback path is not the same as control path: chair back/seat

- Chair Turret
    - To use rotatable chair to steer left/right direction
- "AirPix"-like controller
    - AirPix transforms vision from tactile feel of airflow decided by road situation, but it's not a controller.
    - AirPix can be combined with gesture/voice recognition technology to create a controller with haptic feedback through airflow.
    - The role of gesture/voice recognition in car is more applied in car communication/navigation/entertainment so as to improve driving safety [24].
- A controller that can take use of gravity, magnetic, shape-change, air pressure, etc.
    - Shape-change is an interesting point that could be explored. The Team discussed about to use a balloon as the controller, and the control signal could be the change of its shape.

Placement of controller in car

In terms of placement of the controller in PanaEVE car, several elements were considered, categorized as below.

- Whether it's physical controller or virtual controller
- Whether it's movable or not (restrictedly movable or possible to "pack & go")

Types of haptic feedback

In terms of what kind of haptic feedback should/could be involved in the controller, several feedbacks were considered as listed below.

- Torque/force feedback
    - Pressure feedback (different from a point force, pressure can be applied throughout a certain area)
- Vibration (it's also a kind of force feedback with different a feeling)
- Optical feedback
- Auditory feedback
- Temperature feedback

Besides, the Team also questioned about whether haptic feedback is needed at all in certain circumstances during the driving, and whether or not the road torque/force that the driver receives from mechanical steering system an optimized one for driving experience.

4.3 Selection of a controller for prototyping

To sum up the information the Team gathered, several diagrams were created in order to map useful information to PanaEVE project.

Figure 17 shows the brainstorming of types of the controller and potential requirements for the controller.

Figure 17: Diagram of brainstorming results for controller types and potential requirements for the controller

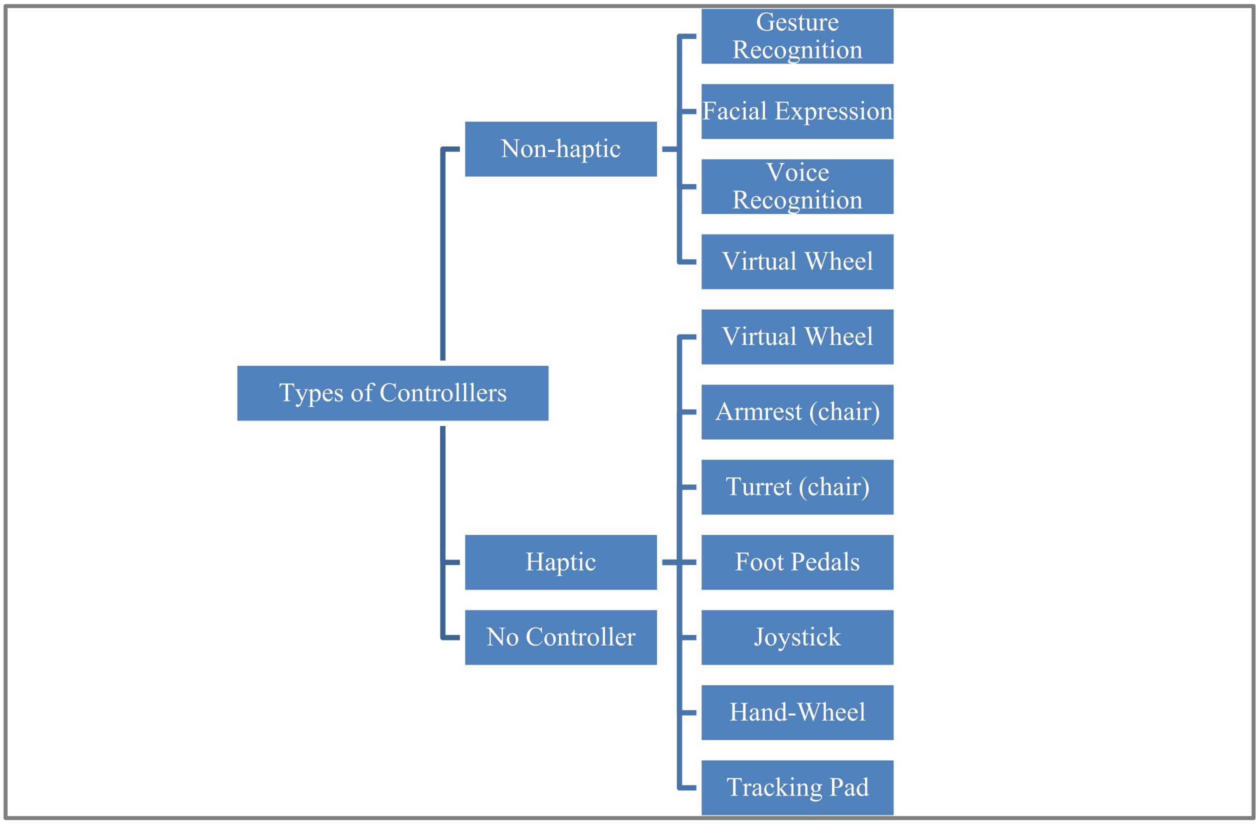

Figure 18: Types of controllers considered for PanaEVE automobile

Figure 18: Types of controllers considered for PanaEVE automobile shows different types of controllers that have been chosen based on the background of PanaEVE project and resources the Team had, and Table 2: Potential Functional Requirements, Physical Requirements and User Requirements shows the potential requirements that retrieved from the diagram in Figure 17: Diagram of brainstorming results for controller types and potential requirements for the controller, which have laid foundation for future prototyping and user-testing.

Table 2: Potential Functional Requirements, Physical Requirements and User Requirements

Potential Functional Requirements	Potential Physical Requirements	Potential User Requirements
• Manual + Automatic (Dual Mode) • Eco-Driving • Multi-functional (the controller can be used for functions other than driving) • Multi-tasks (user can do different tasks while driving) • Adaptive wthin the car	• Unobtrusive / Space-saving • Compatible with other cars • Personalized controllers / Pack & Go • Modular Controller • Conventional / Radical • Minimalist • Simple / Sophisticated	• Thrilling / Engaging Driving • Comfortable Driving • Hands Free Driving • Safe Driving • No Driving

Figure 19 shows a voting diagram of different controllers based on various measurement standards.

Figure 19: Diagram of Voting result for different controllers based on certain measurement standards

Table 3: Scores for different controllers based on certain measurement standards (steering wheel is referenced at 0)

	Space occupied	Design simplicity	Feedback	User effort	Additional Functionality	Customi zability	Learning curve	Know-how in the field	Safety level
Steering wheel	0	0	0	0	0	0	0	0	0
Joystick	2	0	-1	1	-1	1	-1	0	-1
Chair Turret	5	-2	-3	3	3	-3	-3	-4	-4
Virtual wheel	3	-4	-2	-3	-4	2	0	-2	-3
No physical controller	4	-3	-5	-2	2	4	-4	-1	-5
Foot pedals	1	-1	-4	-1	-5	-2	-4	-3	-2
Tracking pad	2	0	-2	-4	-2	3	-2	-2	-2

Table 4: Explanation of different types of controllers

Type of Controller	Explanation
Chair Turret	Swiveling controller with the driver sitting in a chair
Virtual wheel	A 3D hologram that can be controlled, a controller perceived only with glasses
No physical controller	Automatic car, gesture recognition, Voice recognition, face recognition et al
Foot pedals	Any controller operated with feet as opposed to hands
Tracking pad	An iPhone app/ a blind man braille type controller/in general a pad that can be swiped to control the car
Joystick	Generally speaking any one handed/ two handed '3+ DOF stick'

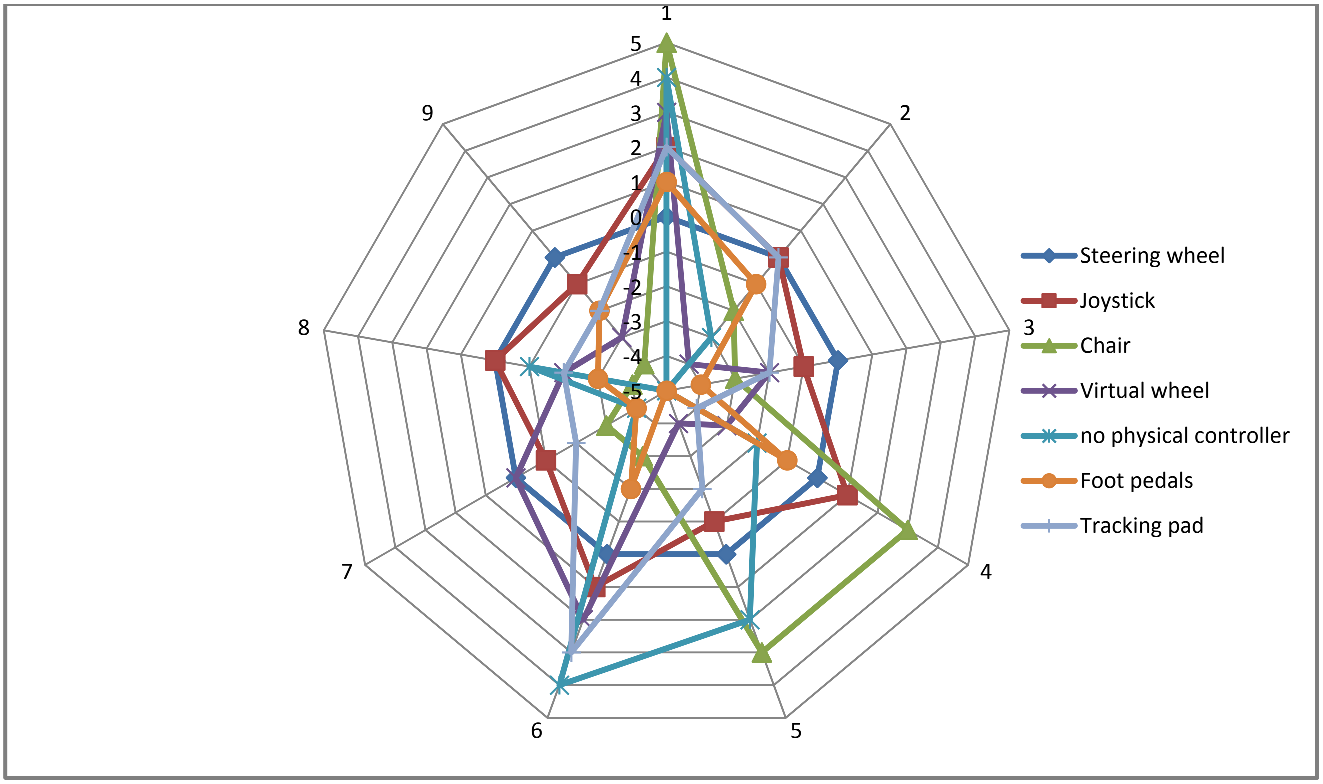

Figure 20: Diagram of comparing different types of controllers based on the scores in Table 3: Scores for different controllers based on certain measurement standards (steering wheel is referenced at 0)

It can be observed from the diagrams that foot pedals get a relatively low score, and some controllers have high fluctuations of scores including chair (turret), no physical controller and virtual wheel. Tracking pad keeps a relatively high score, and joystick keeps average score similar to steering hand-wheel. The high score of tracking pad corresponds to the trend of incorporating smart phone technology with car interior environment, promised by fast development of IT technology. Meanwhile the advantage of joystick is that although its functions don't differ too much with steering hand-wheel, it's more flexible in position & direction and changeable in shape, which enhances the modularity and customizability of joystick. Furthermore, several ideas such as armrest of chair and chair turret are basically transformation of joystick. So the Team decided to look into joystick for prototyping.

4.4 Prototyping

4.4.1 Experiencing joysticks

There are some researches [14] comparing driving experiences with hand-wheel and joystick(s) as documented above. However, the research and experiment didn't study too much into improving the functions of joystick, such as to enhance the joystick system by modifying the mechanism. This gives us some more space to further explore with joysticks.

After the brainstorming of various controllers, the Team decided to first look into the haptic experience with a simple 3D joystick platform, based on Novint Falcon shown in Figure 21: A Novint Falcon and the defined coordinates, which is a USB haptic device intended to replace the mouse in video games and other applications [25].

The Team first explored with N VeNT game software which is the official interface for Novint Falcon to Falcon games, information, software updates, unique content and community [26] , The main user interface of N VeNT software shown in Figure 22: The main user interface of NVeNT software.

Playing with Novint Falcon, the Team found that Falcon is an effective tool for gun-shooting PC games, such as Call of Duty, with an immersive experience of different levels of vibration force feedback. Meanwhile, not many researches have been done to explore the haptic feedback of Falcon for steering control.

There's a driving game called *Rowdy Roady's Road Race* in N VeNT (Figure 23: Rowdy Roady's Road Race game in NVeNT), providing with us the force feedback of road textures. In this game, Falcon can be used as a mouse for left/right direction control, as well as speed-up/brake control when moving falcon forward/back (please refer to Figure 21: A Novint Falcon and the defined coordinates for coordinates reference), without any force feedback of tire/road interactions or other steering assistance. Meanwhile force feedback for different road conditions can be felt as the motorcycle in the game moves from sandy road to highway, simulated by different levels of vibration.

To explore the steering experience of Novint Falcon, The Team played with various open source driving simulators and PC driving games, comparing the experiences with Falcon, Flight Controller (shown in Figure 28: Control Need for Speed game with "T-Hotas Flight controller) and mouse without any force feedback.

Novint Falcon is mainly connected to computer with a USB connector and a Novint-developed software emulator called F-Gen [27]. By modifying F-Gen scripting file, we were able to map Novint Falcon controls to controls of driving simulators, with different levels of force feedback.

Figure 25: The main user interface of F-Gen software shows the main user interface of F-Gen manager.

By the exploring Novint Falcon experience with games and driving simulators, the Team found that the force feedback was very rough and rigid. The experiences showed the need to develop more various force feedbacks for joysticks. Figure 24: A 2D driving simulator [] that the Team played with Novint Falcon and Flight controller. shows a 2D driving simulator that the Team played with Novint Falcon as well as the flight controller. Figure 27: Vdrift open source driving simulator controlled with Novint Falcon shows playing an open source driving simulator Vdrift controlled with Novint Falcon.

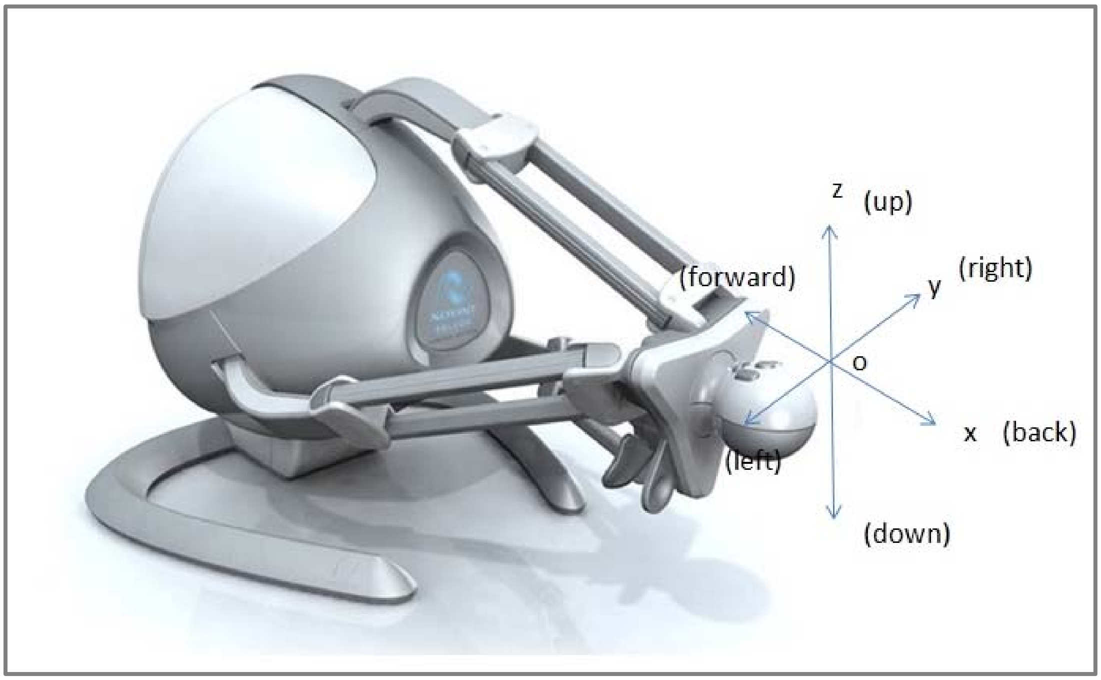

Figure 21: A Novint Falcon and the defined coordinates

Figure 22: The main user interface of NVeNT software

Figure 23: Rowdy Roady's Road Race game in NVeNT

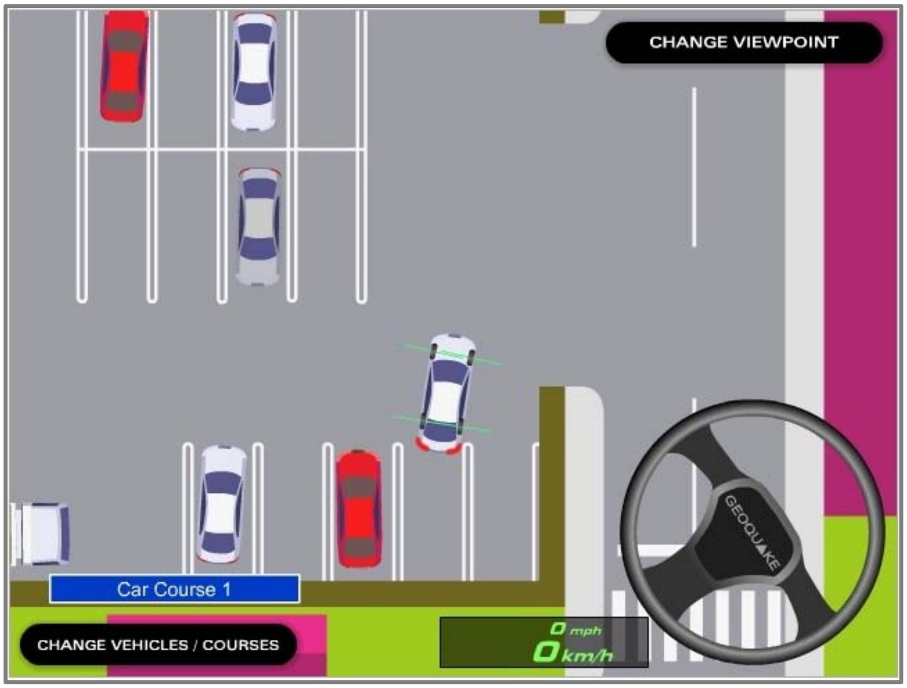

Figure 24: A 2D driving simulator [28] that the Team played with Novint Falcon and Flight controller.

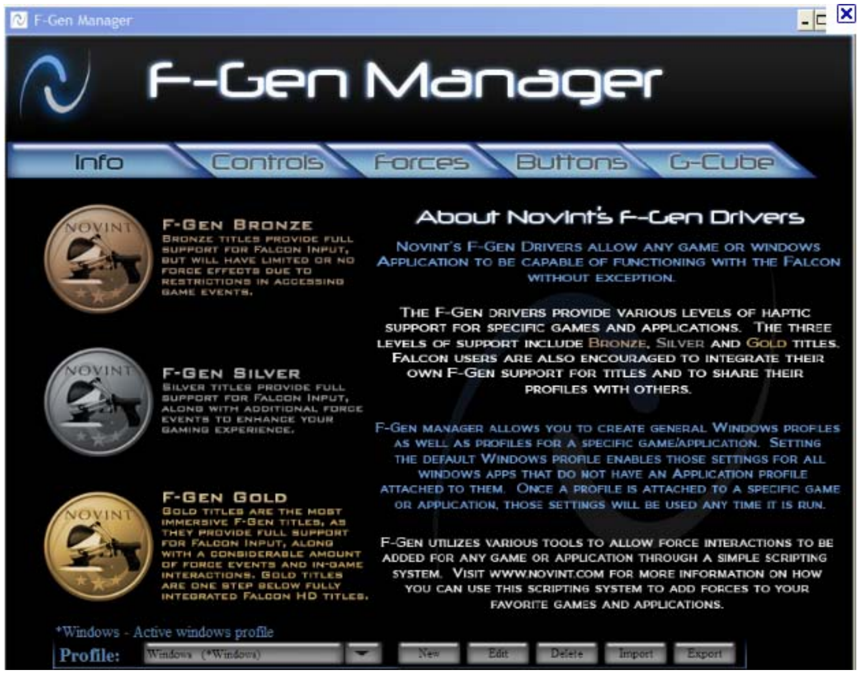

Figure 25: The main user interface of F-Gen software

The PC joystick for flight controller is connected to computer with a USB connector and a keyboard emulator software called JoyToKey [29]. Figure 26: JoyToKey software enables to control driving simulators with "T-Hotas Flight Controller5 shows the main user interface of JoyToKey that enables us to use a flight controller to control automobiles in driving simulators.

The main exploration in this experience was to map different functions of the flight controller, such as translational movement in different directions and rotational movement to the left/right, to left/right turnings, accelerating and braking functions in the driving simulator. These experiments showed very different user experiences for different control commands, which indicated great potential of control with joysticks.

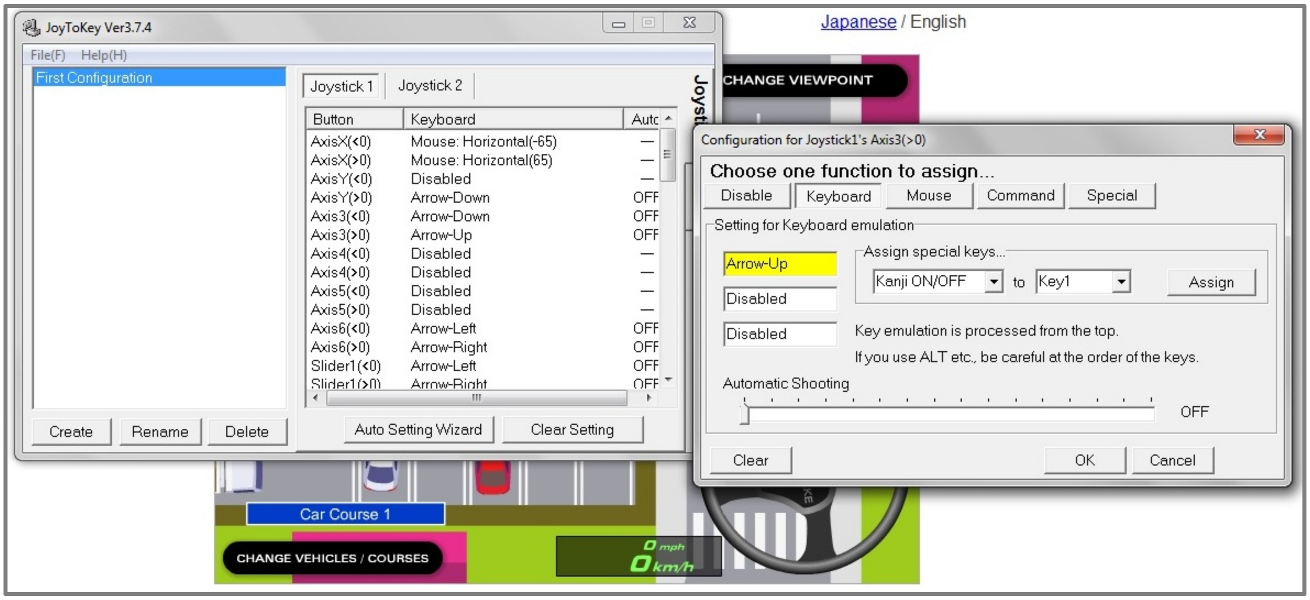

Figure 26: JoyToKey software enables to control driving simulators with “T-Hotas Flight Controller”

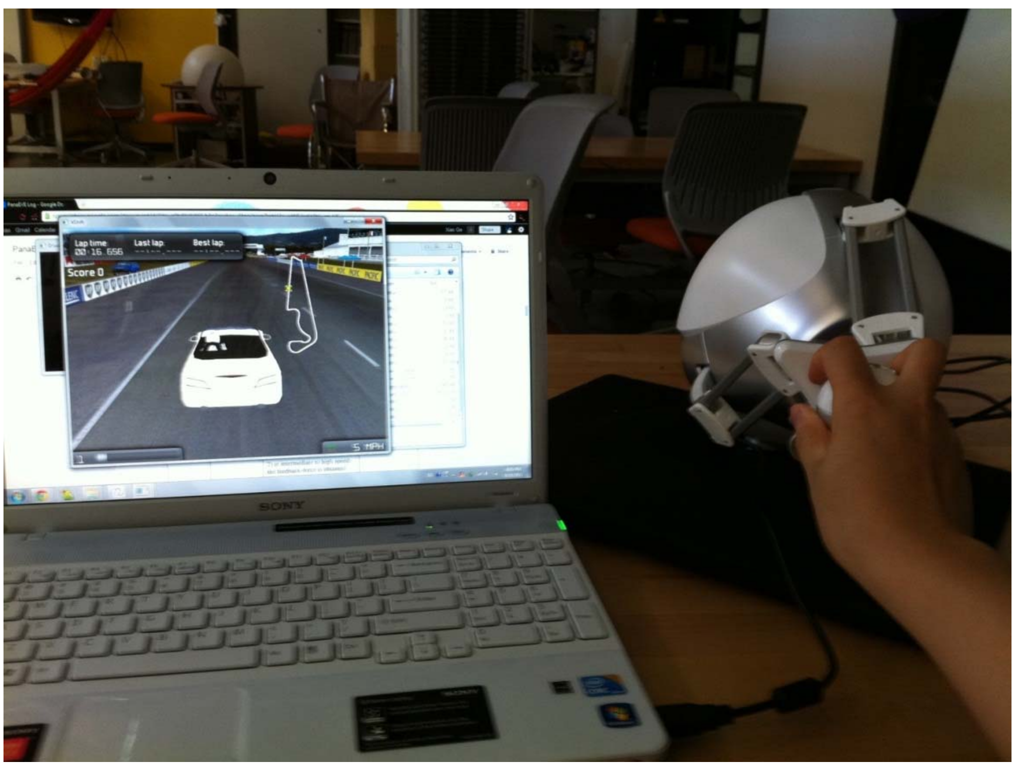

Figure 27: Vdrift open source driving simulator controlled with Novint Falcon

Figure 28: Control Need for Speed game with “T-Hotas Flight controller”

In the prototyping stage, to evaluate the prototypes the Team built, a suitable driving simulator is needed to study drivers' behavior in various road situations with a spectrum of parameter adjustments and settings. Designing driving simulators is mainly a problem of dealing with astutely combining sensory illusions and sensory substitutions with technological solutions [1]. The Team has tried one driving simulation platform in CHIMe Lab with traditional hand-wheel as steering system. Unfortunately, the Team hasn’t made the progress to test prototypes with the driving simulation platform. However, based on the experiences joysticks with open-resource simulators, the Team concluded that it would be easy to test prototypes and analyze results with a simple simulator with adjustable parameters and settings.

With an open-resource library set CHAI3D, the Team started prototyping by building a simple simulation interface to test with Novint Falcon. The initial goal for this prototyping practice is to build a simulator with different combinations of haptic feedback functions, and utilize the simulator to test with more controllers that the Team brainstormed in the earlier stage.

4.4.2 Falcon 1.0 (Proportional force control)

The purpose of building a simulator is to make it simple and straightforward in order to evaluate the haptic feedback by Novint Falcon. For future work, the simulator can also be utilized for designed controllers with built-in motor to provide haptic feedback. The simulator is developed within an open source set of libraries called CHAI3D [30].

Figure 29: Main user interface shows how proportional force control of Falcon 1.0 works shows the main user interface about how proportional force control of Falcon 1.0 works. A simple road lane is created with a blue cursor representing the car. The Virtual Haptic Device control box replaces the haptic device Novint Falcon when the simulator controlled with mouse. Here, in order to show the force amplitude and position of the cursor, this control box is enabled. The coordinate system is also marked in the figure. Figure 30: A closer view of cursor located at the center lane, with zero force feedback shows a closer view of cursor located at the center lane, with zero force feedback.

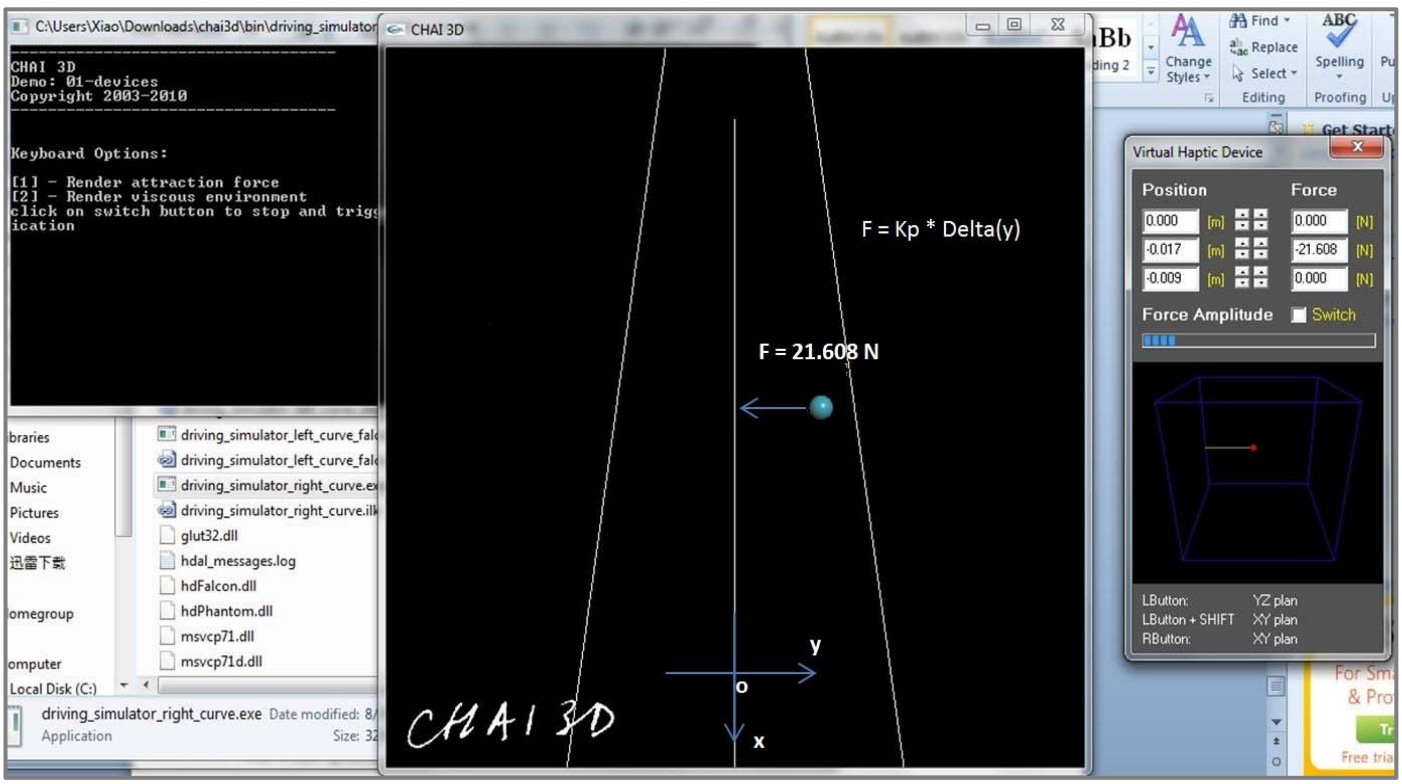

Figure 29: Main user interface shows how proportional force control of Falcon 1.0 works

In this driving simulator, the Team assumed that the force/torque feedback of tire/road interaction was enabled, based on which a lane-keeping assistance system was created with different kind of user experiences.

Two navigation strategies were designed. In Navigation Strategy 1(Figure 31: Navigation Strategy 1 - the navigation line keeps in the center of road lane as the cursor moves into curve part), the navigation line, which is the zero-force line, follows the center of road lane as the road curves. This navigation strategy aims at a more autonomous driving experience. Meanwhile, in Figure 32: Navigation Strategy 2 - the navigation line keeps the same as the straight part when the cursor moves into curve part, Navigation Strategy 2 shows that the navigation line doesn’t change when the cursor enters the curve part. This navigation strategy simulates the traditional mechanical driving experience. The two navigation strategies shows two completely different user experiences, and provide valuable choices for future researches.

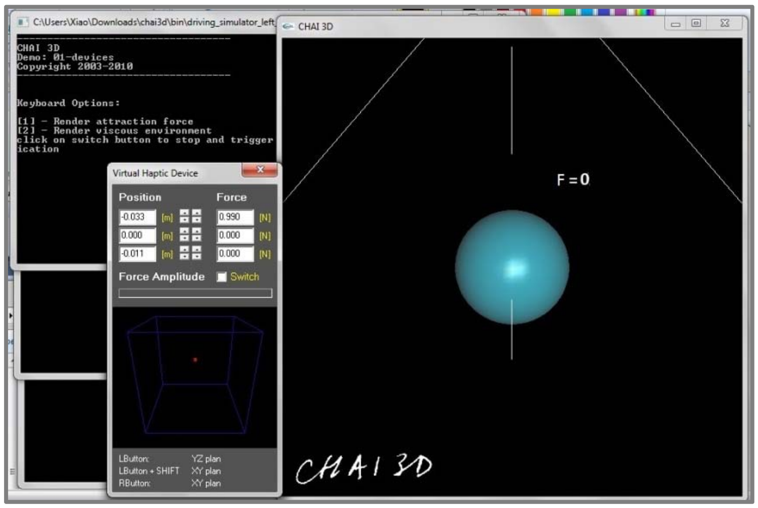

Figure 30: A closer view of cursor located at the center lane, with zero force feedback

Besides, two different camera views of the simulator were developed as shown in Figure 30: A closer view of cursor located at the center lane, with zero force feedbackand Figure 33: An alternative camera view showing the road lane in perspective of the driver. One version of the camera views is designed to move parallel with the moving of Falcon knob. Another version is designed to enable a rotation camera view as Falcon knob is moved sideways, which is more realistic in driving situation. The later version of camera view needs future work to be improved due to time limitation.

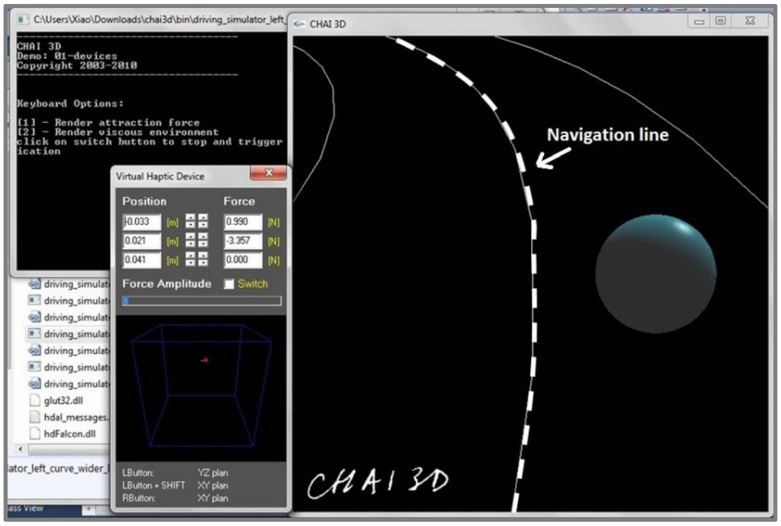

Figure 31: Navigation Strategy 1 - the navigation line keeps in the center of road lane as the cursor moves into curve part

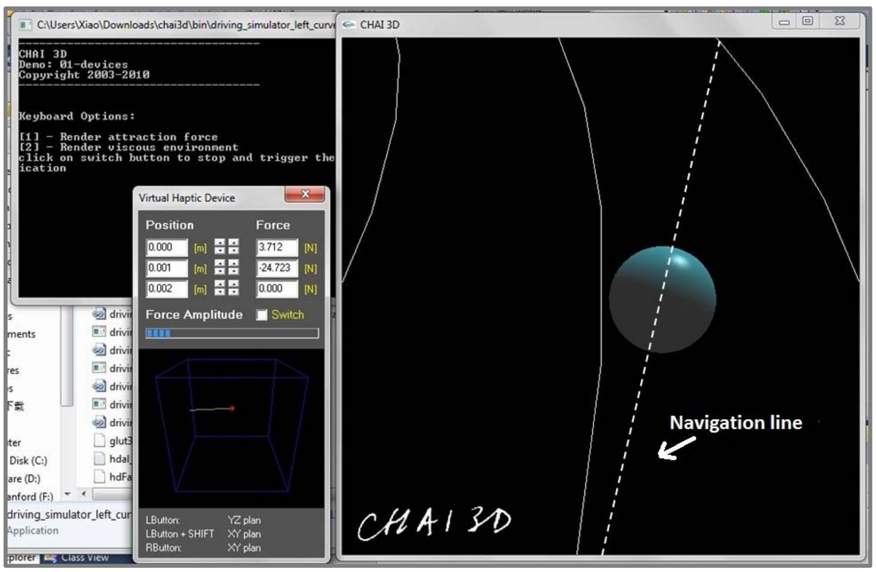

Figure 32: Navigation Strategy 2 - the navigation line keeps the same as the straight part when the cursor moves into curve part

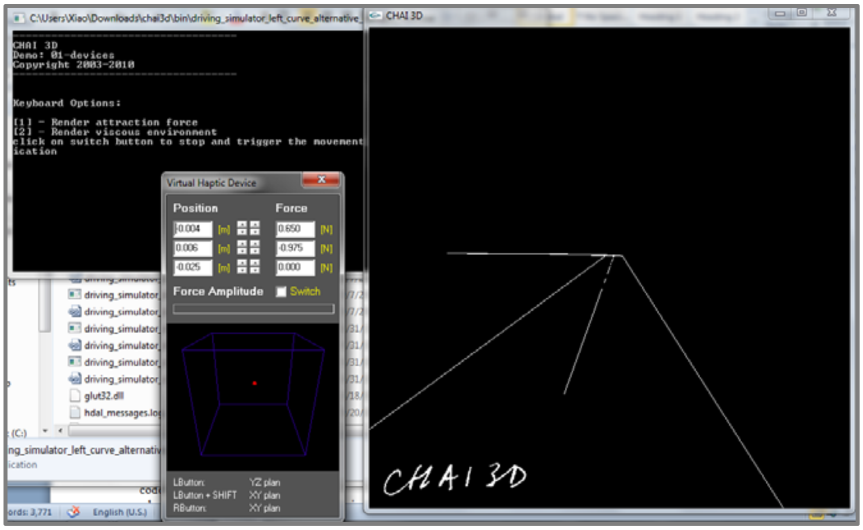

Figure 33: An alternative camera view showing the road lane in perspective of the driver

Based on the first trial of Falcon1.0, The Team had several findings. The experiment with proportional force control of Falcon 1.0 showed a certain range of vibrations of force feedback. A PID controller was called in needed. Furthermore, since the Novint Falcon has 3 degrees of freedom, while the simulator only enabled 2 degrees of freedom, the extra freedom of Novint Falcon bothered the control for users using Falcon. Also, it provided different user experiences to map control commands of simulator to different coordinates of Novint Falcon, positioning Falcon in different directions.

4.4.3 Falcon 1.1 (proportional force with x restraint)

As concluded in the previous section, the extra freedom of Novint Falcon bothered the control for users using Falcon. In order to remove the extra freedom, two restraint strategies were designed, detailed as below.

a) X Restraint in hardware

Figure 34: Physical Restraint in X coordinates of Novint Falcon with free movement in Y and Z coordinates

Figure 34: Physical Restraint in X coordinates of Novint Falcon with free movement in Y and Z coordinates shows a physical restraint of Novint Falcon's knob movement in X direction. The experiements with this prototype showed a very limited movement in Y-Z plane, due to the limited movement of knob in 3D space. Another reason is that the Y-Z plane was adjusted in X direction (so that X is not equal to 0) to enable a smooth movement, thus the movement of the knob is further limited. The restricted movement experience also limited the feeling of haptic feedback.

b) X Restraint in Software

Figure 35: Software Restraint in X coordinates of Novint Falcon with free movement in Y and Z coordinatesshowed a software restraint of Novint Falcon, by enabling a certain degree of force feedback in the extra degree of freedom (the extra coordinate is X coordinate for Novint Falcon in this experiment). This experiment showed a better experience than Falcon 1.0, without any extra mechanical systems built on Novint Falcon. However, since the movement of Falcon in X coordinate was not eliminated entirely, this strategy needs further improvement for future development. Possible modification could be a combination of restraint in both hardware and software.

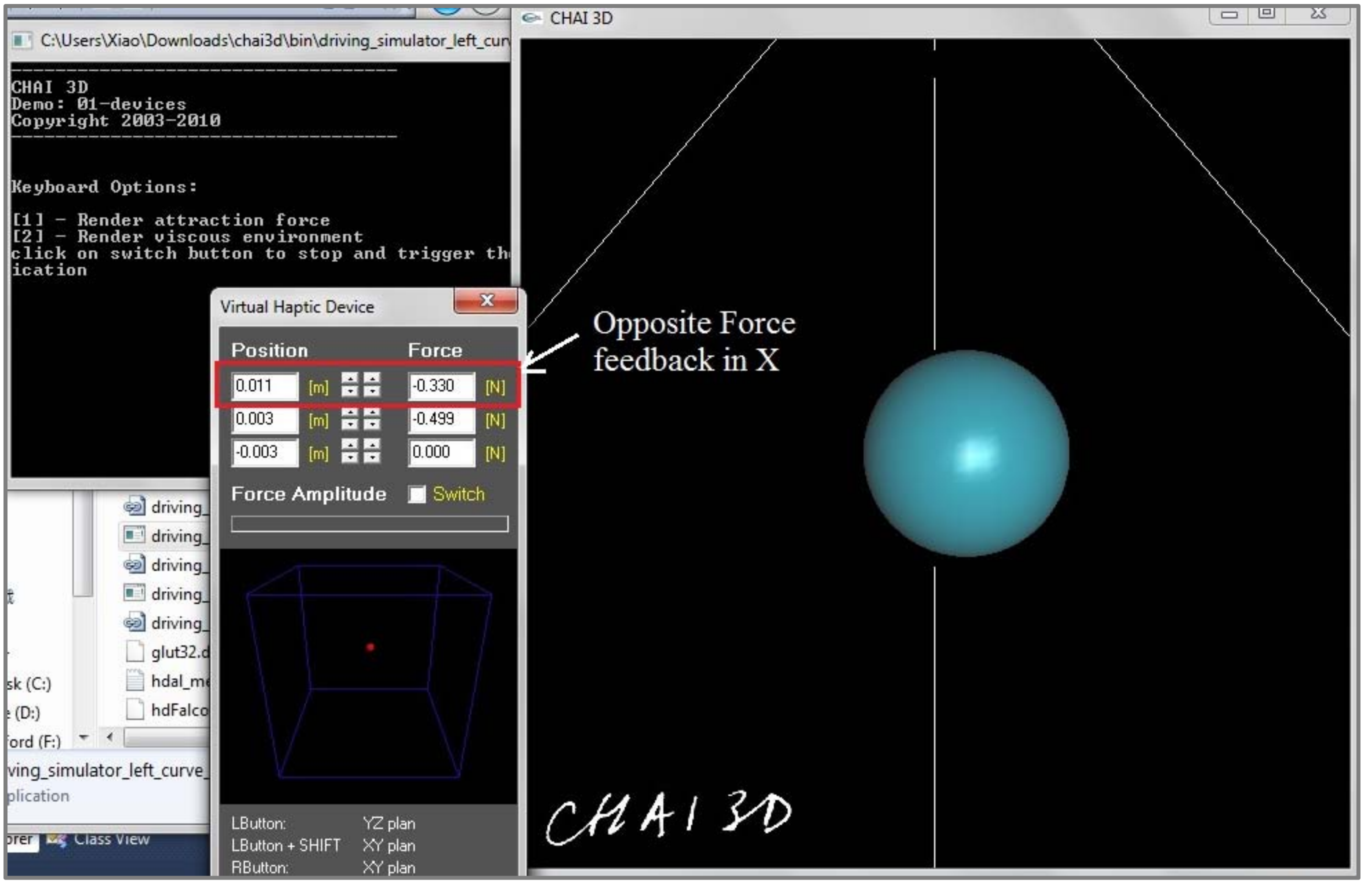

Figure 35: Software Restraint in X coordinates of Novint Falcon with free movement in Y and Z coordinates: as shown in control box, the movement of falcon in X direction caused a force in the opposite direction.

4.4.4 Falcon 2.0 (PID force)

As concluded in 1.3.2, the experiment with only proportional force control of Falcon 1.0 showed a certain range of vibrations of force feedback. In order to improve it, PID controller was applied in the simulator. The experiments with PID controller showed that vibrations of Falcon knob can be avoided with some derivative control. A desirable force feedback was realized with smooth movement of Falcon as it returned to its origin. Integral control didn't add obvious help to the control performance.

4.4.5 Falcon with Two-handed Controller

Figure 36: Two-Handled Handle built on Novint Falcon

During the user-testing of Falcon, it was found that one-hand control was not as desirable as two-hand control. The Team thus built a two-handled controller as shown in Figure 36: Two-Handled Handle built on Novint Falcon. The handle shape simulated a typical aircraft steering controller. The flexibility of the handle on Falcon enabled more space of movement. Meanwhile, two-hand control showed more accurate control than one-hand control.

5 Design Description

5.1 Hardware

5.1.1 Novint Falcon overview

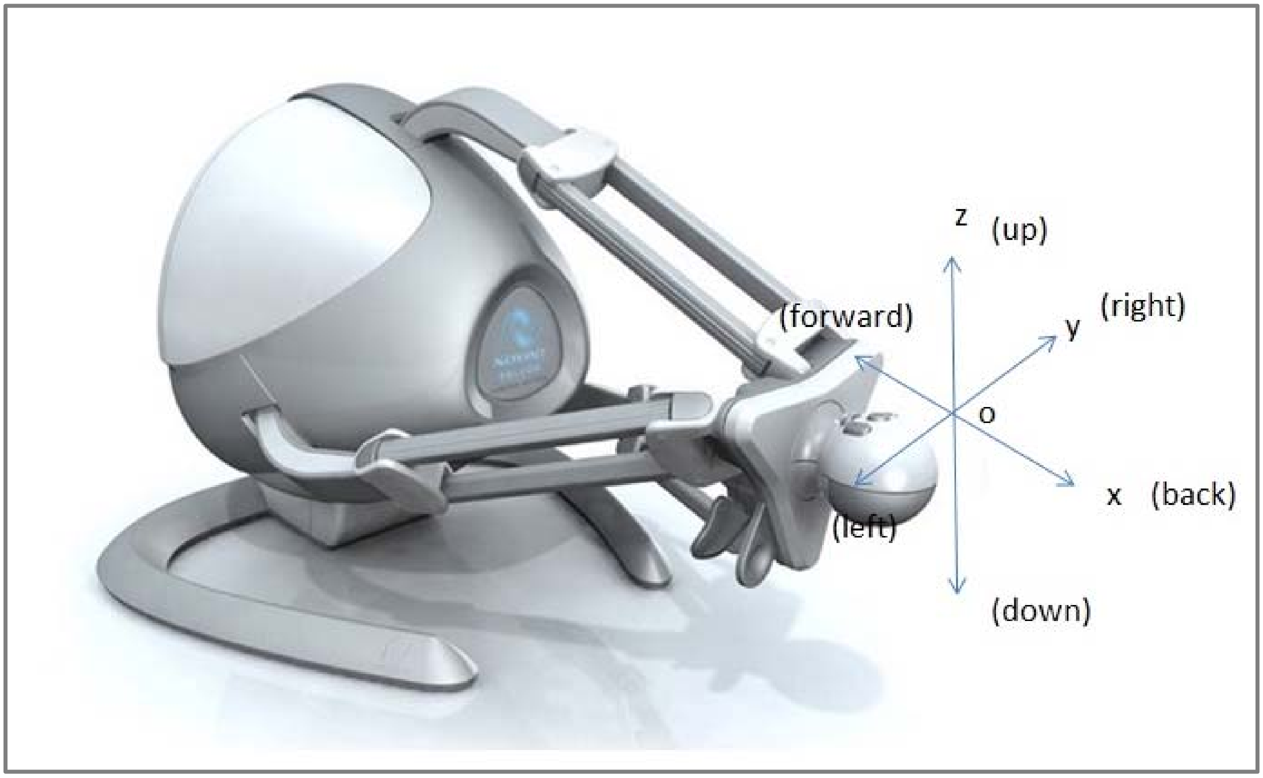

Figure 37: Novint Falcon haptic controller with its degrees of freedom. The axes are representative of naming convention adopted in this study Novint falcon is a 3DOF haptic device developed for immersive gaming. It has 3 translational degrees of freedom and can produce forces along these DOFs in magnitudes exceeding 3 lbs. Its specs are as follows

Novint falcon is a 3DOF haptic device developed for immersive gaming. It has 3 translational degrees of freedom and can produce forces along these DOFs in magnitudes exceeding 3 lbs. Its specs are as follows

<u>Technical Specifications for Novint Falcon</u>

3D Touch Workspace	4" x 4" x 4"
Force Capabilities	2 lbs
Position Resolution	400 dpi
Quick Disconnect Handle	1 second change time
Communication Interface	USB 2.0
Size	9" x 9" x 9"
Weight	6 lbs
Power	30 watts, 100V-240V,50Hz-60Hz

5.1.2 Prototype features

Housing

On getting universal feedback that it is both more intuitive and comfortable to navigate using a joystick moving on a horizontal plane, a fixture was developed for the falcon so that its knob could be moved by a driver on a horizontal plane. (Seated on its default stand, this plane becomes the vertical plane). A narrow slot was provided in the wooden fixture to locate the asymmetric stand. Black electrical tape was used as zip ties to fasten the falcon body to the wooden housing.

The entire fixture was made from scrap wood.

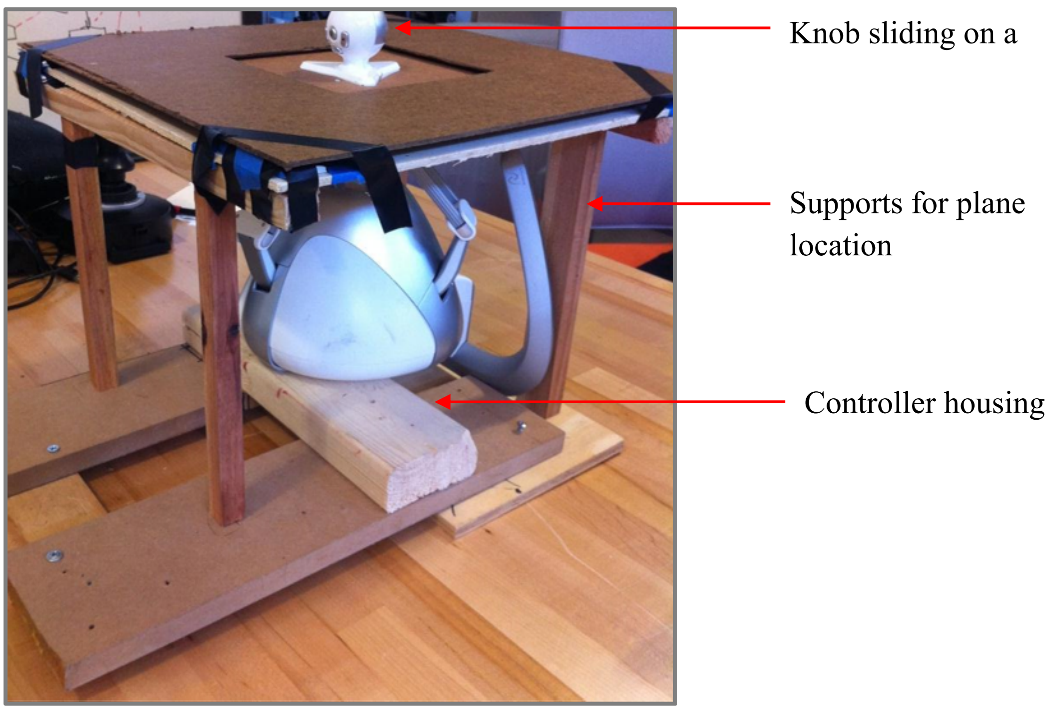

Figure 38: Controller housing – Since the force mechanism interfacing to the knob is not relevant to driver experience, it is housed inside a wooden cover.

"Horn" – for two handed vs. one handed control

Based on feedback from earlier prototypes, the final prototype has a provision for 2 handed control if desired by driver. A 'horn' that serves as a 2 handed grip can be attached and removed easily when shifting between 2 handed and one handed driving. The horn is made of 1 ½" PVC pipes and fittings based on what was most comfortable sized pipe to grip. There is a definite opportunity in making this design more ergonomic for a better grip and if need be, make the horn-falcon joint universal so that drivers can have a custom grip. In this case, the entire controller need not be modular but just the driver drip could be a modular component

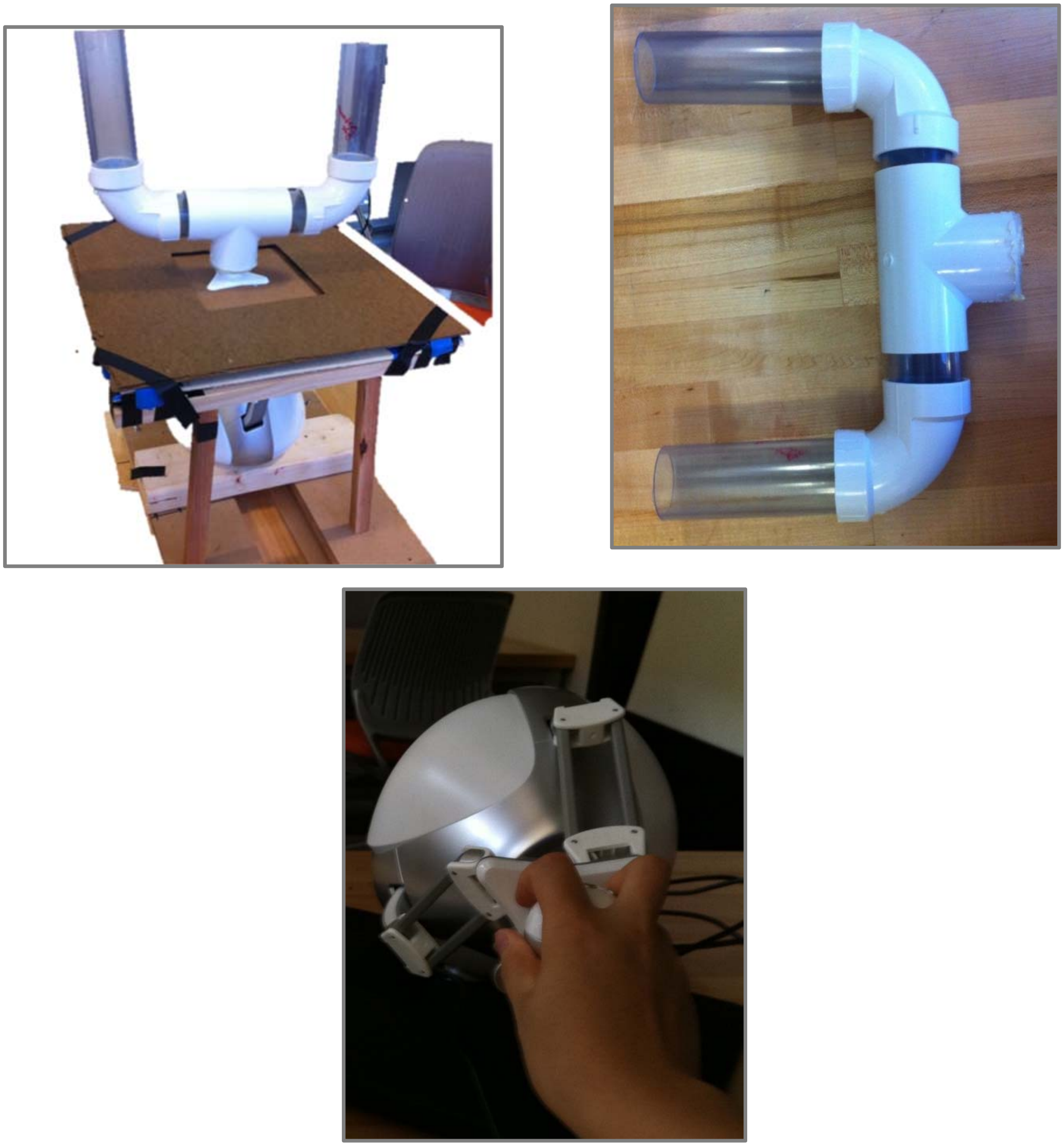

Figure 39: One handed vs. two handed control: Prototype allows driving with one hand as well as both hands

Restraining platform – for preventing motion in X direction

In order to physically restrain superfluous degrees of freedom, a plane was constructed and the falcon knob was restrained to move on that plane. Height of this plane from the bottom dead center of knob was measured off based on what distance gave maximum knob compliance in y and z directions.

Wooden posts were fixed to the base of prototype housing and a 3 layered plate sandwich was rested on top of these posts. The topmost and bottommost layers served as restraints for the knob. The middle layer was attached to the falcon arm (and knob) such that this layer could slide with relatively less adherence between two outer restraining plates.

Middle layer was made from a cardboard sheet whereas restraining plates were made from a thin masonite sheet.

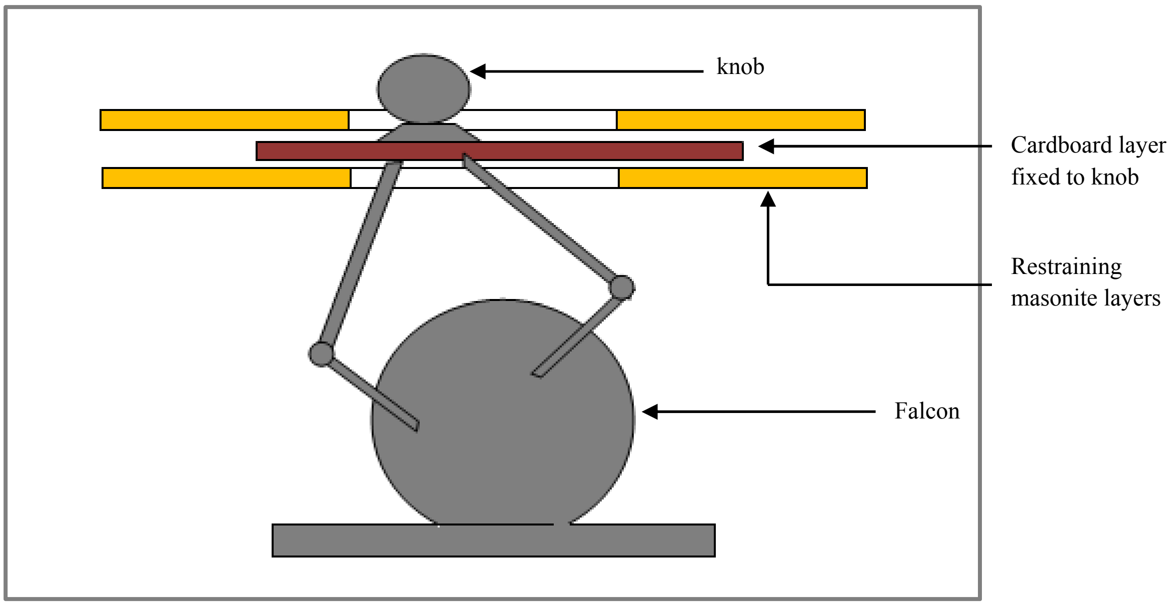

Figure 40: Schematic of the restraining platform

5.2 Software

5.2.1 Coordinate system

World coordinate system is shown in the following figure. Car moves on the X=0 plane. Camera is effectively fixed to the car but moves on the X=0.2 plane and looks down upon the road ahead, this gives a more realistic feel of driving point of view. There are two coordinate systems at play here. X, Y, Z correspond to the global coordinates in the fixed reference frame of the world. x, y, z correspond to the reference frame of the car and hence reference frame of the falcon. It is worth noting that x and X are identical unit vectors corresponding to the unit normal outside the plane determined by the track. Thus z points toward the instantaneous tangent to the lane curve at the cursor position and y points toward the instantaneous normal.

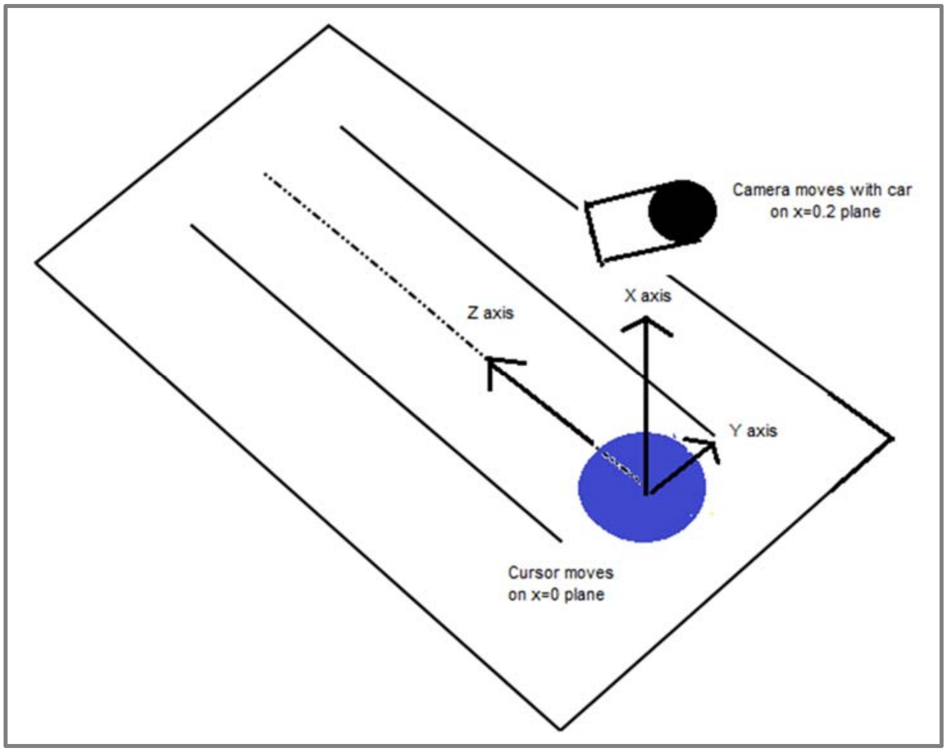

Figure 41: Worldmap – depicting location of the car (cursor image of falcon), camera and the lane with reference to the coordinate axes

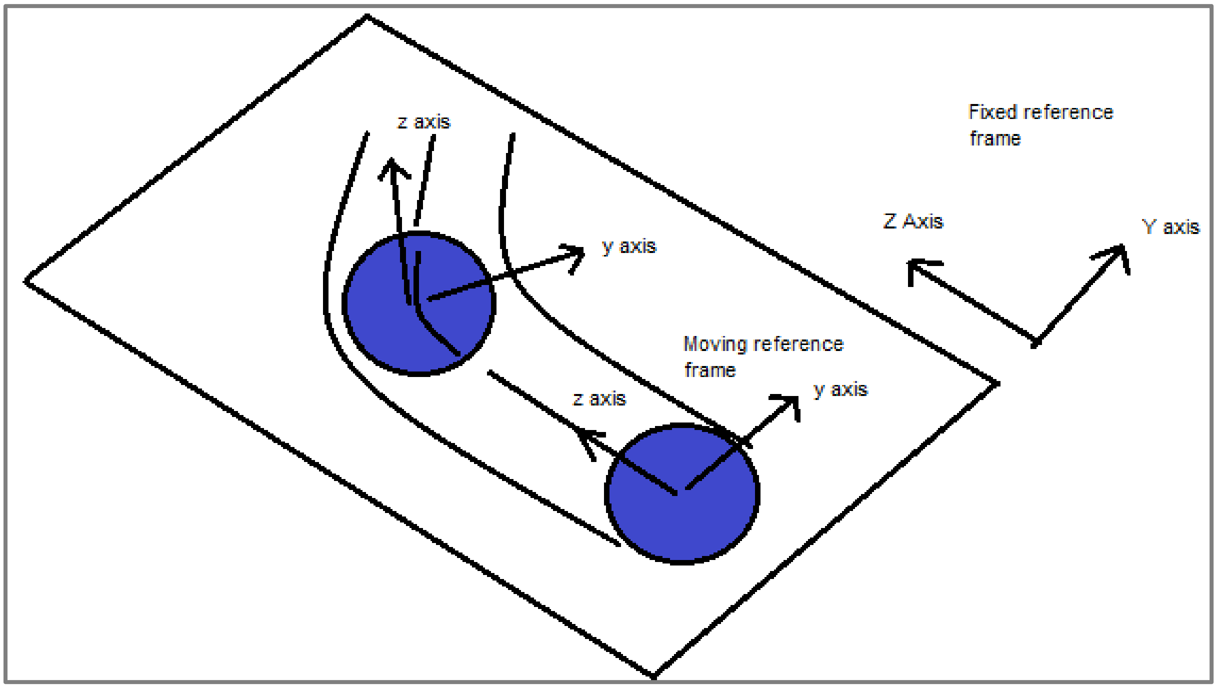

Figure 42: Global and local coordinate systems

5.2.2 World

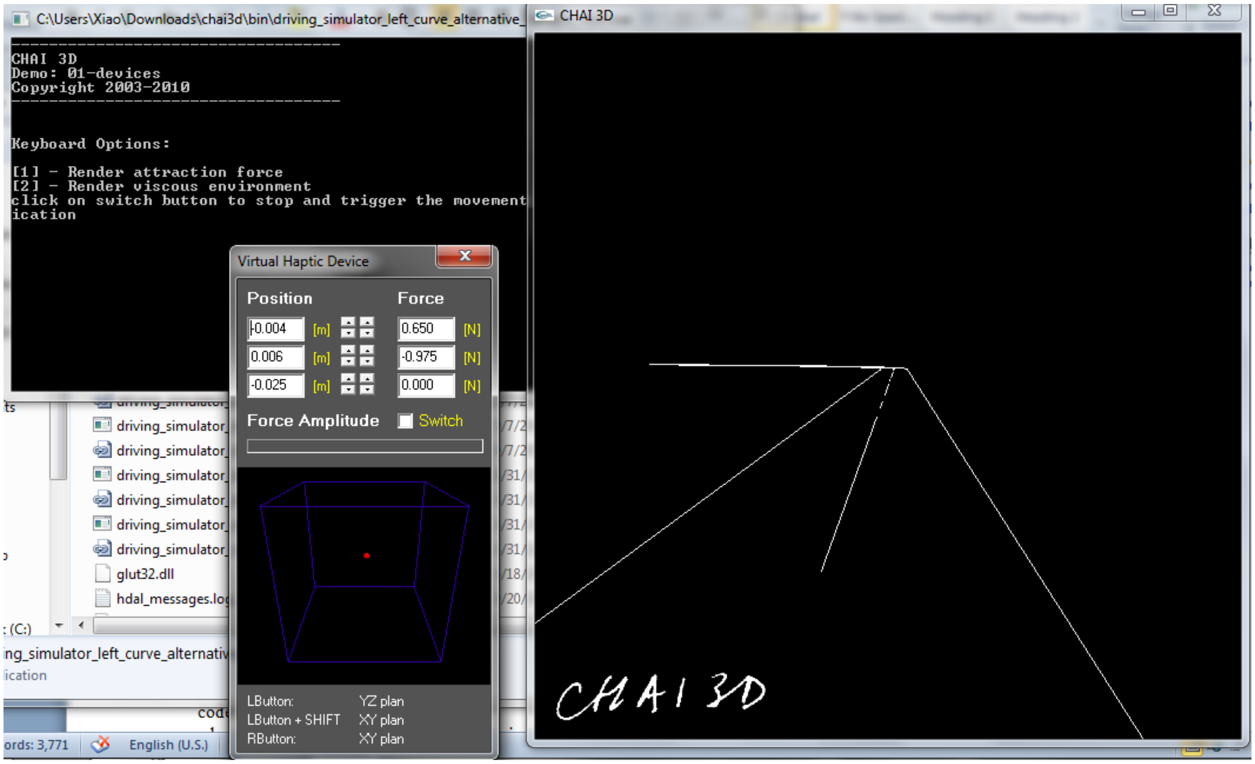

Figure 43: Map of a stretch of straight road followed by a minor curve toward the left. Note that the dotted midline helps in visualizing the car moving forward when the road is straight

5.2.3 Camera

Camera seeks to follow a first person driving experience. Thus, camera y and z position is fixed to the car y and z position at all times. However, in order to be able to get a downward view of the road, the camera movement happens on a plane parallel to the x=0 plane. Offset of this plane is something that can be easily changed depending on test subject preference/test conditions. In our prototype, this offset is fixed at 0.2 units (or half of lane width). The following figure shows some sample views in the simulation

Thus as a summary:

Camera characteristics (in open GL format)

<u>Camera Position</u>: Same as cursor position, on a plane that is 0.2 units above cursor motion plane

<u>Look at position:</u> 0.25 units in front of the cursor along the vector pointing toward instantaneous velocity of the car

<u>Direction of up vector</u>: Unit vector along x axis

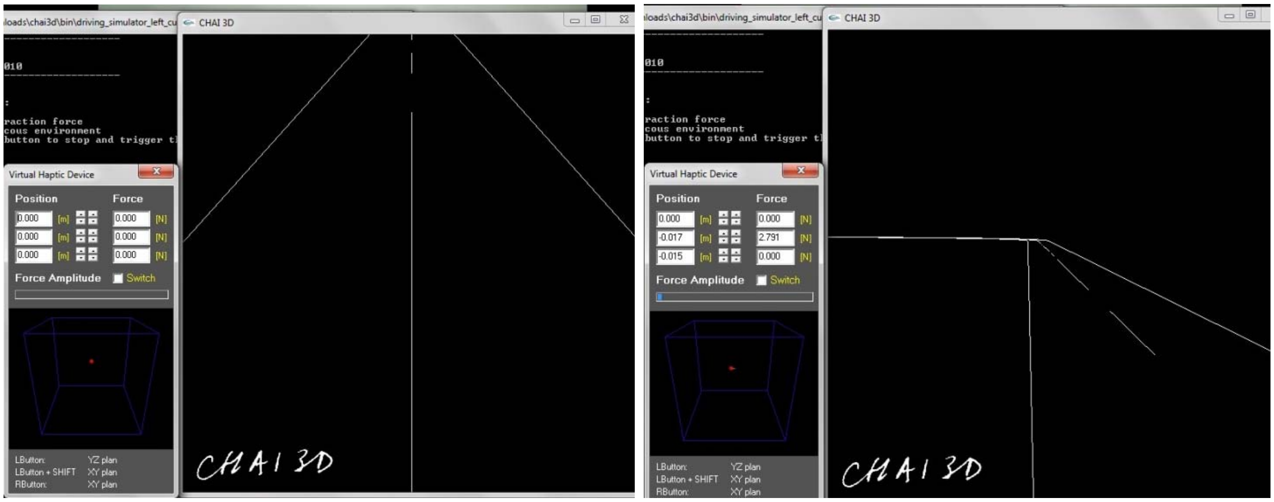

Figure 44: Camera view corresponding to a first person driving effect necessary for simulators

5.2.4 Navigation strategy

In our simulator prototype, it is assumed that line following based on tracking of lane midline is possible. Thus, forward motion of the falcon (along z direction) will propel the cursor in the direction of the lane at all times and cross motion of the falcon (strafing right-left) would move the cursor laterally perpendicular to the lane. Speed of travel will depend on the extent of displacement of falcon from its neutral position along Z direction. Moving falcon knob along –ve z direction would brake the car and persistent deviation along the same direction would put the car into reverse.

Whenever, cursor would leave the lane center line in the lateral direction, haptic forces would kick in to try to bring to bring it back to the center. Figure 43 shows this with a schematic

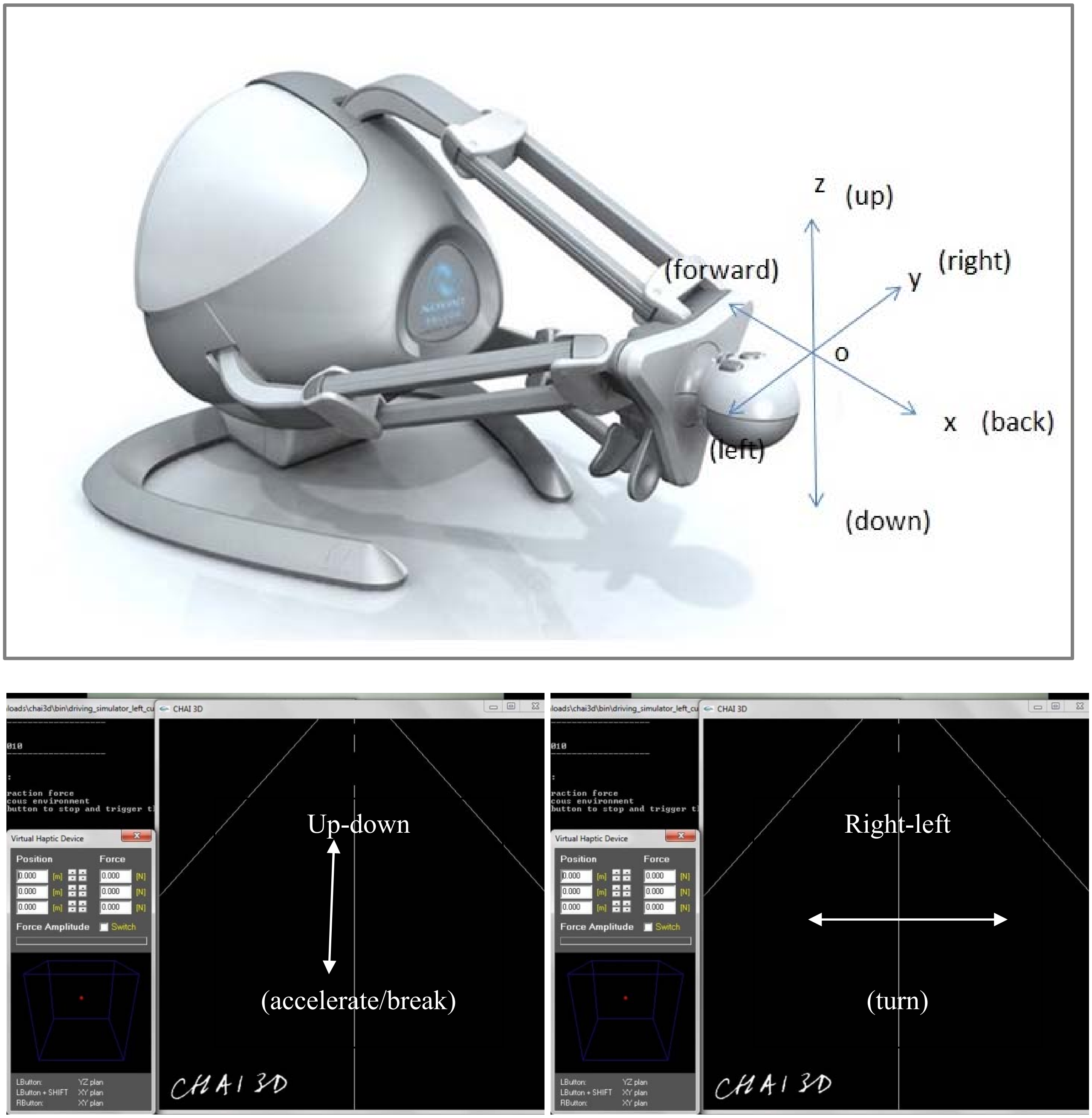

Figure 45: A schematic to show how knob movements map to the virtual world

5.2.5 Haptic feedback (PID control)

According to the lane assist model, haptic force on the driver operating the controller should act in such a way that car would be steered onto the middle of any lane. This is modeled in our prototype by a PID control strategy depending on the deviation of cursor's center from center line of the lane. In a simple proportional controller, this force would translate to just a spring force pulling the cursor toward the center, but with damping and an integral component added to the system, the equations are as follows

As described in the section on coordinate system, local coordinate system fixed with the car corresponds to coordinate system of falcon joystick. Thus, at any point of time, tangent along the track inside the software simulation corresponds to +ve z direction of the falcon knob and normal corresponds to the y direction.

Basic PID equation for lateral force (perpendicular to lane) on driver is -

$$F = -K_p y - K_d \dot{y} - K_i \int y$$

Taking a differential form of this equation-

$$\frac{\Delta \mathrm{F}}{\Delta t} = -K_p \frac{\Delta y}{\Delta t} - K_d \frac{\Delta \dot{y}}{\Delta t} - K_i y$$

which simplifies to this recursive equation -

$$New\ force_y = Old\ force_y - K_p(y_{new} - y_{old}) - K_d(v_{y,new} - v_{y,old}) - K_i y \Delta t$$

Velocity at any instant can be calculated from a CHAI3D library function for the Novint Falcon. Thus, if Force is initialized at time t=0, force magnitude can be calculated at any instant of time with the above formula

5.2.6 "Virtual detent" along x axis

In order to prevent knob motion in the x direction, there is a provision in software in case the rigid constraint provided by the prototype fixture is cumbersome for driving experience. This is a simple reimplementation of the haptic force formula along y direction for x direction. Knob motion out of plane (along x direction) gives rise to restoring forces that drive it back to x=0 plane making this a 'Neutral detent in software'

$$New\ force_x = Old\ force_x - K_p(y_{new} - y_{old}) - K_d(v_{y,new} - v_{y,old}) - K_i y \Delta t$$

6 Future Potential of Concept

6.1 Future Prototyping

The Team has established a simulation framework with CHAI3D library set, on which several iterations of prototypes were tested and evaluated. In addition to the simulation framework, the Team has also built several mechanical systems based on Novint Falcon. Some user-testing results are inspiring for building steering systems based on joysticks in the future. The core system of the code executes lane assistance to virtual steer-by-wire car driving. The simulation code modules are promising for building more sophisticated simulation models in the future. Several suggestions are concluded and listed here.

- There are two navigation choices of the simulator as described in the document. More experiments and further development can be done in the future to improve and evaluate the navigation strategies for better driving experience.
- Based on current rotating model of camera view (to rotate the camera view of the car while moving joystick(s) sideways), the model can be improved to satisfy multiple driving conditions, as well as in combination of navigation strategies.
- The simulator is built in 2D and has been kept as simple as possible. In the future, 3D models can be built to make the driving experience more realistic. The exploration work of the extra degree of freedom of joystick is also promising.
- As for application of the simulator, future work can be to connect different controllers, such as steering wheel with feedback motor attached to its shaft, with the simulator using Arduino talking to CHAI3D.

It has been proven in this project that, a joystick steering system is promising in steer-by-wire automobile in the future. Transformation of joystick(s) can be developed to satisfy specific automobile systems. Meanwhile, as was discussed in benchmarking and brainstorming stages, some other ideas, such as Virtual Reality and Sensory Substitution can be taken into consideration for the design of Haptic Steering system.

6.2 Future Application

The automobile market in 2020 has shown a trend of “driving in modules”. Modularity and Customizability will be enormously explored to form an emerging driving behavior, in which driving can be a process of “plugging”. This trend can be predicted by a lot of researches in platooning, the trend of carpooling, increased application of intelligent systems and small cars. The prospect is promising that all a driver does for driving from one place to another is to shift between different automobile modes with evasive maneuvering, hence the need for joysticks.

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8 Appendix

8.1 Chai3D Documentation

8.2 Code

8.2 Curve Lane Values

curve lane

width of lane = 0.6

left line	radius = 2.5	mid line	radius = 2.6	right line	radius = 2.7
x	y	x	y	x	y
-4	-0.3	-4	0	-4	0.3
-3.88	-0.303	-3.8651	-0.0034	-3.8501	0.2963
-3.7604	-0.312	-3.7304	-0.0135	-3.7005	0.285
-3.6413	-0.3269	-3.5965	-0.0303	-3.5517	0.2663
-3.5232	-0.3478	-3.4636	-0.0538	-3.404	0.2402
-3.4062	-0.3746	-3.332	-0.0839	-3.2578	0.2067
-3.2908	-0.4072	-3.2021	-0.1206	-3.1134	0.166
-3.177	-0.4455	-3.0742	-0.1637	-2.9713	0.1181
-3.0654	-0.4895	-2.9486	-0.2131	-2.8317	0.0632
-2.9561	-0.5389	-2.8256	-0.2688	-2.6951	0.0013
-2.8494	-0.5938	-2.7056	-0.3305	-2.5617	-0.0673
-2.7456	-0.6539	-2.5887	-0.3982	-2.4319	-0.1424
-2.6449	-0.7192	-2.4755	-0.4716	-2.3061	-0.224
-2.5476	-0.7894	-2.366	-0.5506	-2.1844	-0.3117
-2.4539	-0.8644	-2.2606	-0.6349	-2.0673	-0.4055
-2.3641	-0.9439	-2.1596	-0.7244	-1.9551	-0.5049
-2.2783	-1.0279	-2.0631	-0.8189	-1.8479	-0.6099
-2.1969	-1.116	-1.9715	-0.918	-1.7462	-0.7201
-2.12	-1.2081	-1.885	-1.0217	-1.65	-0.8352
-2.0478	-1.304	-1.8038	-1.1295	-1.5598	-0.955
-1.9805	-1.4033	-1.728	-1.2412	-1.4756	-1.0791
-1.9182	-1.5058	-1.658	-1.3566	-1.3977	-1.2073
-1.8611	-1.6114	-1.5937	-1.4753	-1.3264	-1.3392
-1.8094	-1.7196	-1.5355	-1.5971	-1.2617	-1.4745
-1.7631	-1.8303	-1.4835	-1.7216	-1.2039	-1.6129
-1.7224	-1.9432	-1.4377	-1.8486	-1.153	-1.754
-1.6875	-2.058	-1.3984	-1.9778	-1.1093	-1.8975
-1.6583	-2.1744	-1.3655	-2.1087	-1.0728	-2.043
-1.6349	-2.2921	-1.3393	-2.2411	-1.0437	-2.1901
-1.6175	-2.4108	-1.3197	-2.3746	-1.0219	-2.3385
-1.606	-2.5302	-1.3068	-2.509	-1.0075	-2.4878
-1.6005	-2.6501	-1.3006	-2.6439	-1.0006	-2.6376
-1.601	-2.7701	-1.3012	-2.7788	-1.0013	-2.7876
-1.6075	-2.8899	-1.3085	-2.9136	-1.0094	-2.9374
-1.62	-3.0092	-1.3225	-3.0479	-1.025	-3.0865
-1.6384	-3.1278	-1.3432	-3.1813	-1.048	-3.2347
-1.6628	-3.2453	-1.3706	-3.3134	-1.0785	-3.3816
-1.6929	-3.3614	-1.4046	-3.4441	-1.1162	-3.5268
-1.7289	-3.4759	-1.445	-3.5729	-1.1611	-3.6699
-1.7705	-3.5884	-1.4918	-3.6995	-1.2131	-3.8105
-1.8177	-3.6988	-1.5449	-3.8236	-1.2721	-3.9484
-1.8703	-3.8066	-1.6041	-3.9449	-1.3379	-4.0832
-1.9283	-3.9116	-1.6693	-4.0631	-1.4104	-4.2145
-1.9914	-4.0137	-1.7404	-4.1779	-1.4893	-4.3421
-2.0596	-4.1124	-1.8171	-4.289	-1.5745	-4.4655
-2.1326	-4.2076	-1.8992	-4.3961	-1.6658	-4.5845
-2.2103	-4.2991	-1.9866	-4.4989	-1.7629	-4.6988
-2.2925	-4.3865	-2.079	-4.5973	-1.8656	-4.8081
-2.3789	-4.4697	-2.1762	-4.691	-1.9736	-4.9122
-2.4694	-4.5486	-2.278	-4.7796	-2.0867	-5.0107
-2.5637	-4.6227	-2.3841	-4.8631	-2.2046	-5.1034
-2.6616	-4.6921	-2.4943	-4.9411	-2.3269	-5.1902

-2.7628	-4.7565	-2.6081	-5.0136	-2.4535	-5.2707
-2.8671	-4.8158	-2.7255	-5.0803	-2.5839	-5.3447
-2.9743	-4.8698	-2.8461	-5.141	-2.7179	-5.4122
-3.084	-4.9183	-2.9695	-5.1956	-2.855	-5.4729
-3.196	-4.9613	-3.0955	-5.244	-2.995	-5.5267
-3.3101	-4.9987	-3.2238	-5.286	-3.1376	-5.5734
-3.4258	-5.0303	-3.354	-5.3216	-3.2823	-5.6129
-3.543	-5.0561	-3.4859	-5.3506	-3.4287	-5.6451
-3.6613	-5.076	-3.619	-5.373	-3.5766	-5.67
-3.7805	-5.0899	-3.753	-5.3887	-3.7256	-5.6874
-3.9002	-5.0979	-3.8877	-5.3977	-3.8753	-5.6974
-4.0202	-5.0999	-4.0227	-5.3999	-4.0252	-5.6999
-4.1401	-5.0959	-4.1576	-5.3954	-4.1751	-5.6949
-4.2597	-5.0859	-4.2921	-5.3842	-4.3246	-5.6824
-4.3786	-5.07	-4.4259	-5.3662	-4.4732	-5.6624
-4.4966	-5.0481	-4.5586	-5.3416	-4.6207	-5.6351
-4.6133	-5.0203	-4.69	-5.3104	-4.7666	-5.6004
-4.7285	-4.9868	-4.8196	-5.2726	-4.9106	-5.5585
-4.8419	-4.9475	-4.9471	-5.2284	-5.0523	-5.5094
-4.9532	-4.9026	-5.0723	-5.1779	-5.1914	-5.4533
-5.062	-4.8522	-5.1948	-5.1212	-5.3276	-5.3903
-5.1683	-4.7965	-5.3143	-5.0585	-5.4604	-5.3206
-5.2716	-4.7354	-5.4306	-4.9899	-5.5895	-5.2443
-5.3717	-4.6693	-5.5432	-4.9155	-5.7147	-5.1617
-5.4685	-4.5983	-5.652	-4.8356	-5.8356	-5.0729
-5.5615	-4.5226	-5.7567	-4.7504	-5.9519	-4.9782
-5.6506	-4.4422	-5.857	-4.66	-6.0633	-4.8778
-5.7357	-4.3576	-5.9526	-4.5648	-6.1696	-4.772
-5.8163	-4.2687	-6.0434	-4.4648	-6.2704	-4.6609
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-5.9639	-4.0796	-6.2093	-4.252	-6.4548	-4.4245
-6.0304	-3.9797	-6.2842	-4.1397	-6.538	-4.2996
-6.0918	-3.8766	-6.3533	-4.0237	-6.6147	-4.1708
-6.148	-3.7706	-6.4165	-3.9044	-6.685	-4.0383
-6.1988	-3.6619	-6.4736	-3.7822	-6.7485	-3.9024
-6.2441	-3.5508	-6.5246	-3.6572	-6.8052	-3.7635
-6.2838	-3.4376	-6.5693	-3.5298	-6.8548	-3.622
-6.3179	-3.3225	-6.6076	-3.4003	-6.8973	-3.4782
-6.3461	-3.2059	-6.6393	-3.2691	-6.9326	-3.3324
-6.3684	-3.088	-6.6645	-3.1365	-6.9605	-3.185
-6.3849	-2.9692	-6.683	-3.0028	-6.9811	-3.0365
-6.3953	-2.8496	-6.6947	-2.8683	-6.9942	-2.887
-6.3998	-2.7297	-6.6998	-2.7334	-6.9998	-2.7372
-6.3983	-2.6098	-6.6981	-2.5985	-6.9979	-2.5872
-6.3908	-2.49	-6.6896	-2.4638	-6.9885	-2.4375
-6.3773	-2.3708	-6.6745	-2.3296	-6.9716	-2.2885
-6.3579	-2.2524	-6.6526	-2.1964	-6.9474	-2.1405
-6.3326	-2.1351	-6.6241	-2.0645	-6.9157	-1.9939
-6.3014	-2.0192	-6.5891	-1.9341	-6.8768	-1.849
-6.2645	-1.905	-6.5476	-1.8057	-6.8306	-1.7063
-6.222	-1.7929	-6.4997	-1.6795	-6.7774	-1.5661
-6.1738	-1.6829	-6.4456	-1.5558	-6.7173	-1.4287
-6.1203	-1.5756	-6.3853	-1.435	-6.6504	-1.2944
-6.0614	-1.471	-6.3191	-1.3174	-6.5768	-1.1637
-5.9974	-1.3695	-6.2471	-1.2032	-6.4968	-1.0369
-5.9284	-1.2713	-6.1695	-1.0928	-6.4106	-0.9142

-5.8546	-1.1767	-6.0865	-0.9863	-6.3183	-0.7959
-5.7762	-1.0859	-5.9982	-0.8842	-6.2202	-0.6824
-5.6933	-0.9992	-5.905	-0.7866	-6.1166	-0.574
-5.6062	-0.9167	-5.8069	-0.6938	-6.0077	-0.4709
-5.515	-0.8386	-5.7044	-0.606	-5.8938	-0.3733
-5.4201	-0.7652	-5.5976	-0.5234	-5.7751	-0.2816
-5.3216	-0.6967	-5.4869	-0.4463	-5.6521	-0.1959
-5.2199	-0.6331	-5.3724	-0.3748	-5.5248	-0.1164
-5.115	-0.5748	-5.2544	-0.3091	-5.3938	-0.0434
-5.0074	-0.5217	-5.1334	-0.2494	-5.2593	0.0229
-4.8973	-0.4741	-5.0095	-0.1958	-5.1216	0.0824
-4.7849	-0.432	-4.883	-0.1485	-4.9812	0.135
-4.6706	-0.3956	-4.7544	-0.1075	-4.8382	0.1805
-4.5546	-0.365	-4.6239	-0.0731	-4.6932	0.2188
-4.4372	-0.3402	-4.4918	-0.0452	-4.5465	0.2498
-4.3187	-0.3213	-4.3585	-0.0239	-4.3984	0.2734
-4.1994	-0.3083	-4.2243	-0.0093	-4.2493	0.2896
-4.0796	-0.3013	-4.0896	-0.0015	-4.0995	0.2983
-3.9596	-0.3003	-3.9546	-0.0004	-3.9496	0.2996