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Master's Thesis
Academic Year 2018

Reinvent Steering Wheel An Examination on Automobile Steering Interface and Renovation Proposition for Vehicle Cockpit Ergonomics

Keio University
Graduate School of Media Design

ShaoAn TSAI

A Master's Thesis
submitted to Keio University Graduate School of Media Design
in partial fulfillment of the requirements for the degree of
MASTER of Media Design

ShaoAn TSAI

Thesis Committee:

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Abstract of Master's Thesis of Academic Year 2018

Reinvent Steering Wheel An Examination on Automobile Steering Interface and Renovation Proposition for Vehicle Cockpit Ergonomics

Category: Science / Engineering

Summary

Automobile steering interface has remained unchanged for more than a century. This research analyzed its mechanism and human motion pattern to identify the input factors and characteristics, and proposed few hypotheses and a new concept for automobile steering interface. Experiments were also conducted utilizing correspondingly designed apparatus to examine driver behavior in given set of conditions. The goal of this research is to proposes a new steering method, in hope of a more effortless and intuitive interaction between the driver and the vehicle whilst retaining the merits of current automobile steering mechanism. Equally importantly, by repackaging of drivers seat and dashboard with the proposed new steering method, this research tries to exploit and improve current automobile cockpit space allocation and limitation.

Keywords:

Human-Machine Interface, Automobile, Steering, ADAS

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Chapter 1
Introduction

1.1 Background

Automobile steering system came into resemblance to its modern form and architecture around 1900 [15]. Ever since, steering wheel as an user interface has seen little change. Remaining same in form and similar in function, steering wheel dominates as common human-machine interface in passenger vehicles and in most commercial vehicles to this day.

Steering wheel takes in binary input and produce binary result; rotating direction dictates steering direction. In regards to magnitude, the more the driver rotates the steering wheel, the bigger the steering angle at the front wheels. This stunningly simple and effective human-machine interface has long endured. Moreover, steering wheel naturally holds certain characteristics that add to functionality. Being a circular rim, steering wheel avoids problem of arm fatigue. When driving straight, driver's hands are placed symmetrically on the steering wheel. By doing so, the torque generated by hand pull from both hands due to gravity cancels out, and the steering wheel remain force balanced. Thereby the steering wheel effectively serves as an acting point for the arms, exempting the driver's arms from fatigue.

Steering wheel also provides certain level of slack to the drivers thanks to its straight line stability resulted from front suspension setup. When driving on long straights, it is common that drivers rest their arms on the laps or alongside the door window corner, with only slight grip on the steering wheel, despite this is most likely not taught in driving schools nor suggested by any driving guideline.

In the long history of automobile development, various additional auxiliaries had been invented to further empowering steering wheel. From straightforward functional integration including indicator switches, wiper switch, horn, and various dashboard function controls, to Advanced Driver Assistance System such as power-steering, airbag unit, variable steering ratio, drive-by-wire, driver fatigue detection, etc. But regardless of all the advancement in terms of functionality, steering wheel remains the same in terms of human-machine interface: Its form, working mechanism, physical setup have virtually seen no change at all.

1.2 Problem Identification

Before discussing further, we ought to examine the human-machine interaction of automobile steering interface. There are three ways of human-machine interaction in automobile steering interface, referred as 'steering techniques' by National Highway Traffic Safety Administration (NHTSA) of the United States of America.

Hand-to-Hand Steering, or Push/Pull Steering is recommended as universal steering technique. with this method, the driver grips the steering wheel 3'o clock and 9'o clock of the steering wheel. When initiating a turn, the driver first moves both his hands to top of the steering wheel, then based on the direction he intends to go, he firmly grabs the steering wheel with the hand on the steering direction and pull down the wheel so the wheel rotates in that direction, while his other hand slide down on the other side at same speed without gripping the wheel. Based on the amount of steering needed, if the hands meet at the bottom of the steering wheel and more steering wheel rotation is needed, the hands switch grip: The originally sliding hand now firmly holds the steering wheel and rotate it upward, while the opposing hand looses grip and slide up the steering wheel. This process goes on until either the driver reaches desired steering angle or deadlock. With this method, the steering wheel rim are virtually split in half, and the driver moves his left and right hands along the left and right semicircular curve. The driver never takes his hands off the steering wheel, nor are his arms ever crossing each other.

Another technique is named Hand-over-Hand Steering. With this method, the driver places his hands at 3 o'clock and 9 o'clock of the steering wheel, and rotates the steering wheel as he steers the vehicles. As turning radius increases, the driver keeps rotating the steering wheel and reaches the point where he is not able to rotate anymore due to arm joint limitation. To continue for more steering angle, the driver releases the hand opposite to the direction the vehicle is traveling to, moving that hand to right above the gripping hand and re-grip the steering wheel. The driver can repeat this process until he reaches desired steering angle or deadlock. This method is only recommended by NHTSA for 'turning at low speeds with limited visibility at an intersection or when parking the vehicle or recovering from a skid'. The reason for this recommendation is not stated but it can be induced that with this steering method, the driver would tangle his arms during steering maneuver, which brings potential risk in the case of crash accident when the steering column assembly breaks or when airbag deployed.

Still another steering technique exists, known as One Hand Steering. With this method the driver controls the steering wheel by holding it using only one of his hands. Driver instruction by TOYOTA [21] illustrates how this method works. In the illustration the driver seemly press his palms on the steering wheel rim. Steering wheel maneuver can still be achieved by using friction force to keep the driver's palm at the same spot while rotating the steering wheel at the same time. NHTSA only recommends using this method when reversing the vehicle, or when the driver needs to operate on-board controls with the other hand.

With its human-machine interaction clarified, working principles and traits of automobile steering interface can be induced. Using steering wheel as input device, the driver steers vehicle travel direction by rotating the steering wheel left and right. From a pure mechanical view, steering wheel is a planar circular rim pivoted perpendicular to a shaft at its center, and is capable of limited revolutions. Steering wheel produces output with only one input: Its axial rotation. As the rotational input is generated by human hands, and human arms are regarded as of 7 degrees of freedom, we shall further examine upper limb motion in different steering scenarios.

With Hand-to-Hand steering, as the driver steers by sliding his hands between 0 o'clock and 6 o'clock of the steering wheel, his left and right hands always remain on left and right half portions of the steering wheel respectively. This method mainly makes use of wrist joint rotation during the driver's hand sliding motion.

In Hand-over-Hand Steering, as aforementioned in Technical Review, the driver would release hand and re-grip the steering wheel to continue rotating the steering wheel in the case when steering angle exceeds certain threshold. This is due to shoulder joint and elbow joint limitation, and physical limitation of the arms. What's worth noting is before the driver releases his hand, when he still maneuvers the steering wheel with both hands at 9 o'clock and 3 o'clock. Before continuing, for convenience, let's define inner hand as the hand on the same side the vehicle is steering to, outer hand as the hand on the opposite side. For example, in leftward steering scenario, inner hand would be left hand, and outer hand would be right hand. Now as steering angle increases, the driver's inner hand retracts towards torso, while his outer hand stretches to steer towards vehicle travel direction. This motion continues until the driver reaches his joint limits: Mainly due to his inner hand wrist twist, and his left and right arms eventually cross as he steers further. It can be said that in Hand-over-Hand Steering, there exists an effective range where the driver maneuvers the steering wheel by pointing mode. To elaborate, let's draw a vector from center of steering wheel to 0 o'clock on the rim. The driver holds the steering wheel with his hands placed symmetrically at 9 o'clock and 3 o'clock, it could be viewed in a way that the driver steers the vehicle by rotating this steering vector and points it towards desired vehicle travel direction. Furthermore, although with all steering techniques the drivers hands remain on the same plane - the plane cutting though the steering wheel circle.

These two phenomena of Hand-over-Hand Steering imply further limitation. The imaginary steering vector combined with hands serve as good visual indicator for steering wheel maneuvering, however this only works for a short effective range, roughly between -90° to 90° of imaginary steering vector rotation. On the other hand, the driver's hands being physically limited by the steering wheel to a fixed planar circular trajectory hinders ergonomics. As the driver's hands are fixed at 9 o'clock and 3 o'clock positions and move along a pivoted planar circular trajectory, his inner arm continues retracting while his outer hand keeps stretching. While it does not pose an issue to outer hand it seriously limits both inner hand steering torque input and ergonomics. Since outer hand draws a circular trajectory, it stretches and starts to retract as it passes the farthest point on circular trajectory, but inner hand soon reaches its wrist twisting limit, and then the shoulder joint rotational limit. Inner hand torque input to the steering wheel also decreases, until to the point when the driver crosses his hands, and release and move his inner hand to re-grip the steering wheel.

1.3 Scope and Goal of This Research

In previous section, limitation of current automobile steering interface human-machine interaction has been identified. While Hand-to-Hand Steering is considered safety-compliant and recommended by the officials, it lacks intuition, since the driver input action does not directly map to the result, which is vehicle travel direction change. On the other hand Hand-over-Hand Steering is intuitive by considering steering maneuver as pointing an imaginary steering vector towards vehicle travel direction, however this is only effective for a short range of steering wheel rotation. Furthermore, the driver's hands are restricted to a fixed planar circular trajectory, which combined with arm joint limits impede ergonomics and partially contributes to the limitation of Hand-over-Hand Steering steering technique.

Aiming at providing an alternative solution to improve human-machine interaction for automobile steering interface, this research will first examine and analyze the identified limitation further, and propose revision for the human-machine interaction and steering device.

1.4 Structure

In following chapters, firstly past research and practical solutions from automakers and industry suppliers will be reviewed in Chapter 2. In Chapter 3 research method will be explained, and concept for a new automobile steering interface will be proposed. Chapter 4 will go into detail of research method and result discussion. Chapter 5 will demonstrate the new steering interface design and its simulated performance, and conclude this study.

Chapter 2
Literature Review

2.1 Basics of Automobile Steering System

Few types of steering linkage system exist, but the most common type among road vehicles nowadays is rack-and-pinion type. It can be broken down into the following elements: steering wheel, steering column, steering rack, and front wheels. Steering wheel serves as human-machine interface between the driver and the car. The driver interprets visual information and rotates the steering wheel to change travel direction of the vehicle. As the driver inputs and rotates the steering wheel, this rotational movement also rotates the steering column, which is essentially a shaft with one end fixed to center of the steering wheel, while the other end is fitted with gear, and meshes with the steering rack. Steering rack is a gear rack mounted between the front axle, with separate tie-rods connecting its both ends to left and right wheel hubs respectively.

When steering column rotates, it acts as a pinion and transform its rotational movement to linear motion at the steering rack. The steering rack displaces either towards left wheel or right wheel, and the jointed linkages pull one wheel and push the other wheel subsequently. The vehicle thus steers left or right, depending on counterclockwise or clockwise rotational input at the steering wheel.

While steering wheel input is ultimately interpreted binary, its user interaction is more complicated. Due to practicality, steering wheel rotation and front wheel steering angle displacement is not 1 to 1 ratio. In practice steering ratio is commonly set between 14 to 20 [15], which translates to 3 5 end-to-end steering wheel revolution. That is, to reach maximum steering angle either leftward or rightward, the driver would rotate the steering wheel for roughly between one and half to two and half revolutions. Since human arm joints are limited in terms of rotational capability, it is apparent that steering wheel maneuvering requires specific techniques. As explained in Chapter 1.2, National Highway Traffic Safety Administration (NHTSA) of the United States of America provided guidelines for steering techniques, and summarized three common steering techniques, Hand-to-Hand Steering, Hand-over-Hand Steering, and One Hand Steering. These steering techniques implied one of the major attractiveness of steering wheel as steering interface: flexibility. Drivers are not forced to keep their hands on the steering wheels at all time, and drivers can still effectively and precisely steer the vehicle without using both hands. Furthermore, due to caster setup at front suspension, modern automobiles tend re-align its front wheels by itself if there is no steering input. With mechanically linked steering system, this characteristics makes steering wheel re-centers itself, and is stable thus requires little control force input when traveling on straight line.

Aforementioned are merely working principle of automobile steering system. With technological advancement, automobile steering system has evolved into much more complex form. Mechanically its design, layout and packaging has complicated due to regulation, geometric limits of vehicle cockpit and engine room, and ergonomics.

Legally, automobile steering mechanism and devices are not confined to the form of steering wheel in relevant regulation. Safety related specification and standards are nonetheless clearly stated and regulated by different governing bodies, and these regulations inevitably affect automobile steering system design. For instances, United Nations Vehicle Regulations No.12 regulates the safety standards for steering column in the case of conflict accident. The UN regulation did not confine steering mechanism to steering wheel, nonetheless it did thoroughly define individual components of steering wheel style steering mechanism, and the requirements for said steering mechanism in the crash test. By the specific requirements, including vehicle crash speed, steering column displacement after the crash, imposed force and acceleration upon the crash, plus electrical shock protection and isolation, electrolyte spill in the case of power steering, the regulation indirectly complicates steering mechanism design. Similarly defined is Australian Design Rule 10/02, which defines the comprising components of steering wheel style steering system, and its required strength under given crash scenario. Japanese equivalent regulation, Road Transport Vehicle Safety Standards in Road Transport Vehicle Law, regulates automobile steering system requirements in article 91 by defining physical conditions that should be met, and in addition incorporates United Nations Regulation No.79 as steering system's technical standards under various test scenarios. Another important fact should be noted is, as steering device is not regulated and confined to the form of steering wheel, neither is steering wheel maneuvering method regulated. Only guidelines such as aforementioned by authorities such as NHTSA, and training from driving schools are provided.

Ergonomics has increasingly played an important role as steering wheel complement. Common driver assistance systems includes power steering, adjustable steering column. These have become standard nowadays, while car manufacturers and Tier 1 suppliers have bring about more advanced Advanced Driver Assistance Systems for automobile steering.

2.2 Advanced Driver Assistance System

A common issue with steering wheel is steering ratio: the amount of front wheel angular displacement in regards to the amount of steering wheel rotation. The amount of steering input required vary based on driving scenarios. When driving on highway, little amount of steering is needed; in urban area, making left/right turns at intersection requires much more steering input, while U-turn and parking usually makes full use of available steering range, which is when steering wheel is rotated until reaching deadlock.

Steering wheel with one fixed steering ratio may not suit all driving scenarios. Urban driving is characterized with constant change of vehicle travel direction. More steering maneuver is required during left/right turns at intersections, U-turns, parking and reversing. Higher steering ratio is thus desired in city driving scenario: With the same amount of steering input, the front wheel angular displacement is larger, the vehicle is thus more responsive to driver's steering input. While in highway driving scenario, steering displacement is relatively much smaller. This is resulted from physics. Trying to input big steering angle would be hard due to counteracting force from the wheels traveling straight at speed. Also, with sudden and tremendous steering input, the vehicle would spin and even lose control due to torque. In such scenario vehicle direction change is limited to changing lanes and adjusting travel direction in minor scale. Moreover, highways are designed as straight lines or very long curves with large curve radius, thus steering angle in high-speed driving scenario is always of minor scale. That is, driver would prefer a less 'sensitive' steering response. The contrast between low speed driving and high speed driving is now clear. While low speed driving scenarios could use up full travel of steering displacement, high speed driving only utilizes very small portion of the total steering displacement. If the steering system is only capable of one steering ratio setup at a time, the driver would have to adapt to different scenarios using an indifferent human-machine interface.

This challenge was first solved in 1960s, but eventually entered market as commercially available solution only after mid 1980s. In the beginning variable steering ratio was still achieved by pure mechanical solution: revised rack-and-pinion gear mechanism. By the 90s electrically powered steering system had incorporated variable steering ratio, variable steering ratio was not anymore purely mechanical, but achieved electromechanically [15]. One such noble invention was Dynamic Steering from Audi. In Audi's system, a specially designed set of planetary gears were fitted in the steering column, connecting the two sections of steering column. This planetary gear set comprised only one sun gear and the ring gear. Whats worth noting was that the sun gear is actually a thin deformable ring that spun around the steering column with roll bearing support in-between, and meshing with the ring gear. The steering column was further connected to a servomotor, so different level of auxiliary force could be applied. When the steering wheel was turned, the servomotor applied torque on the roll bearing and rotates it. Based on the level of torque applied the bearing spins at different speeds, this subsequently deformed the shape of the sun gear to various extent, the sun gear then meshed with the ring gear at different gear ratio. Variable steering ratio was thus achieved. [6].

In 2003, BMW announced its own version of variable steering ration mechanism, BMW Active Steering. Main structural difference between BMW's and Audi's was that BMW utilized electric motors and double planetary gears to achieve variable steering ratio. The planetary gear was integrated into the steering column. An electric motor was attached aside the steering column, its tip at steering rack side was cut into worm gear and meshes with the planetary gears in the steering column. [8] This layout thus allowed input superimposition of both steering wheel input and electric motor input. By adjusting input level from the electric motor, different level of superimposition between steering wheel input and motor input could be harmonized. When steering was only driven by steering wheel input, which would be zero superimposition, the driver would have direct and sensitive steering, which fit the scenario of low speed, city driving. As vehicle speed went up, superimposition level increased, the motor stepped in and input to the planetary gears in steering column, steering ratio increases and steering response became less sensitive. [9]

While above two systems eased the effort needed for steering, and made steering intelligently responsive, Infiniti (Nissan) invented a different solution, Direct Adaptive Steering, also mentioned in its material as "drive-by-wire" [22]. With traditional steering systems, the the steering wheel and the steering rack remained mechanically direct: the steering column transmitted the torque and rotational movement. With this setup, not only the torque from driver input was transmitted to the wheels, but force feedback from the road was also transmitted to the steering wheel, and to the driver. This could cause unpleasant physical feedback to the driver on rough road surfaces, even affecting steering input. For example, bumpy road surfaces could judder the steering wheel, and subsequently required the driver to constantly correct steering direction by rotating the steering wheel back and forth in small scale. The high frequency judder could also lead to driver fatigue.

With Infinitis solution, the mechanical link between steering column and steering rack was normally not connected. Transmission of steering torque is done electronically, while force feedback from road surfaces is first sent to the electronic control units, interpreted and input to steering assistance in the form of mild force feedback as indicator and reminder of road condition. For fail-safe purpose, the mechanical links between the steering column and steering rack still existed, only that they were normally not engaged. In case of detected emergency, the clutch kicked in and steering link was switched to mechanical link, thus the driver was still in control of the vehicle without electronic assistance. Whats interesting with the actual on-board installation was that, due to that this steering system normally operated without mechanical link to the steering rack, and that input was interpreted electronically, infinite steering wheel revolution was possible.

2.3 Notable Variations of Automobile Steering Interface

With all the effort that goes into automobile steering system development, it is still clear that its underlying principles and human-machine interface remain the same. Though, in the history of automobile development, there indeed were attempts to reinvent the wheel. An early experiment was from Ford Motor in 1967, where conventional steering wheel was eliminated and replaced by two rotatable grips [16]. The grips were positioned at opposite sides to the steering column, and mounted low so that when the driver holds the steering grips his arms could be supported by armrests. Steering input was through wrist twisting and rotating the grips, and the steering control assembly was capable of tilt motion, although Ford emphasized on 'easier ingress or egress from the vehicle passenger compartment' as attraction of this feature [16]. Another notable attempt was implementation of drive-by-wire steering on SAAB Prometheus in 1993, an experiment vehicle modified from a 1992 SAAB 9000. At the time, concept of steer-by-wire just received popular attention due to its implementation in commercial aircraft. With its aviation origin, SAAB conducted this experiment to test its feasibility on road vehicles. Moreover, the test vehicle was not installed with traditional steering wheel. Instead, control was input through a device resembling joystick, installed at the lower portion of the center console. As the driver manipulates the joystick, electronic signals are sent to a control box and converted into steering output and further drives the hydraulic system that controls the steering linkage [1]. At the time of its development, the main proposition of this design was safety. Since steering wheel and steering column are inevitably mounted in front of driver's seat, it poses potential safety concern in the case of crash accident [4]. This research was published in 1992, being a part of European research program PROMETHEUS (PROgraMme for a European Traffic of Highest Efficiency and Unprecedented Safety). What's worth noting is, SAAB researchers also suggested "clearer instrument cluster view" and "freedom to design the instrument fascia" as design merit, although for safety concern rather than human-machine interface design as they stated "freedom to re-design the instrument fascia" was meant to "cushion and support the driver in a crash" [1].

Another attempt to renovate automobile steering interface was the Mercedes-Benz R 129, a concept car based on an 1998 Mercedes-Benz SL roadster. It also made use of joystick as steering interface, but unlike SAAB, two joysticks were implemented. One joystick was situated at lower center console, around the position where usually sits gearshift. The other joystick was mounted on the door at arm rest, close to door handle. The two joysticks were symmetrical in shapes, and were integrated with vehicle acceleration and brake functions, as well as other general functions such as horn; the R 129 did not implement foot pedals for acceleration/deceleration.

Conceivably its steering mechanism was different. According to Daimler, steering ratio for road vehicles was roughly 1:20. Converting this ratio to actual steering wheel rotational displacement, steering wheel lock-to-lock displacement on road vehicles usually ranged between 5 to 6 revolutions. That is, maximum left or right turning radius would be around 540 degrees, which would be $2^{1}/_{2}$ steering wheel rotations. The available range of joystick rotation around its pivot was however much narrower, converting it proportionally to steering wheel rotation would not be realistic and reliable for both low speed and high speed driving. Instead, driver input was measured by grip pressure. The driver's hand grip pressure on the joysticks was interpreted as drivers desired steering angle, this value was then input to the mechanical links to steer the car [2]. Variable steering ratio function was also incorporated into the steering mechanism, the on-board computer adjusted mapping between force input and steering output based on vehicle speed.

A more recent joystick solution was proposed by HONDA in 2011. Named Twin Level Steering, the steering interface has two joysticks replacing the steering wheel at its usual position in front of the drivers seat. It was debut by HONDA on its concept car EV-STER in 2011 Tokyo Motor Show. The drivability of the concept was not demonstrated, but HONDA did test the system on a racing kart and on a Formula Dream prototype vehicle. In the test system setup, the two levers were mounted at the side of the driver seat rather than as demonstrated on EV-STER in front of the driver at steering wheel position, and the levers were pivoted longitudinally, thus although it worked also by rotation, but to the drive the motion was backward pulling and forward pushing. This system setup argued on the base of active and contributing muscles in steering maneuver. According to the authors' summary based on the theory of coordinated control exerted by the muscles, back-and-forth steering motion would be more relevant to the actual output muscles among bi-articular muscles. The authors also identified that wrists could easily exert larger output force in back-and-forth direction. The new steering interface was evaluated by cruising tests. Aside from smoother steering output curves, different vehicle trace lines on the track, and improved lap time compared to the data from the same type of vehicles with steering wheel, driver torso and head motion behavioral differences were also noted. While with steering wheel setup the drivers' face moved as his body trunk inclined towards steering direction, their shoulders rose due to steering maneuver and their pelvises rotated due to lateral forces, with lever setup the drivers' body movement were significantly less. It was concluded that compared to steering wheel, one of the advantages with lever setup was decrease in total steering angle.

Chapter 3
Concept Design

In Chapter 1.3, driver motion characteristics of steering wheel were identified. To practically examine and evaluate empirically, let's formulate it concisely as following hypotheses:

- Proportionate hand displacement is not ergonomic for Hand-over-Hand Steering maneuver.
- The hand trajectory of steering maneuver would not stay on a same plane if not restricted.

Above hypotheses also implies themselves as limitation, given that they are proven true. Should these assumed limitation be overcome, a new concept for automotive steering interface can be designed based on the hypotheses.

3.1 Concept Design

Many recent researches have examined human steering motion from the standpoint of upper limb muscle anatomy, as aforementioned HONDA EV-STER Twin Lever Steering System by Takamitsu Tajima, Hideyuki Fujita, Kouichi Sato and Yoshimi Nakasato [19] in Chapter 2.3. While in Mehrabi's doctoral dissertation, a musculoskeletal arm model was proposed to study driver model in different limited condition experiments. [11]. The merit of analyzing steering motion using established upper limb muscle models is that force exertion can be calculated, major contributing muscles can then be identified. In Twin Lever Steering system [19] [20], steering motion was redesigned to be back-and-forth based on upper limb bi-articular muscle mechanism to exert maximum force, compared to steering motion with steering wheel where left and right arms force exertion can be generally regarded as lateral to the torso. To be more precise, the rotational motion is pivoted around shoulder joints and on a two-dimensional plane that is roughly parallel to the torso, which is the two-dimensional plane steering wheel rim falls upon.

This rotational steering motion is another key feature of steering wheel. With steering wheel, the ultimate driver input is rotational input to a centrally pivoted wheel. The driver is actually accommodating rich input source, the upper limbs, to a unitary output, which is planar rotation of a pivoted wheel. With the two hypotheses brought forward at the beginning of this chapter, in addition that considering safety and packaging as crucial factors in terms of practical application, the new concept should not be limited to the mentality of designing a steering wheel substitute. Rather, we should first examine upper limb anatomically and mathematically. As illustrated in Fig. 3.1, let's assume that shoulder joint is a fixed reference point, and consider hand and wrist joint as a single mass point, to simplify the calculation. Assume individual lengths for the two section of upper limb, arm and forearm, upper limb motion can thus be considered as three-dimensional vector rotation. This indicates that, if joint rotation information can be made available, hand position can be calculated. Mathematically, let shoulder be the reference Origin, F be forearm vector, A be arm vector, R be rotation matrix, elbow and hand position can be calculated by below vector rotation operation:

$$ElbowPosition = [R_y(\theta_{shoulder})][R_x(\theta_{shoulder})]\overrightarrow{F}$$
$$HandPosition = [R_y(\theta_{elbow})][R_x(\theta_{elbow})]\overrightarrow{A}$$

To determine hand position, elbow position would need to be calculated first in order to input to vector A in hand position formula. Two-dimensional rotation can be regarded as rotation around z axis. Thus one more axial rotation is needed to complete three-dimensional vector rotation operation. Practically, which two axial rotation to be used can be determined arbitrarily.

Now that we have deconstructed and reconstructed upper limb motion as vector rotation, and hand position can be consequently calculated, it implies that the driver needs no longer be limited to circular motion trajectories as with steering wheel. This important characteristic of this concept design is illustrated in Fig. 3.2. As mentioned in the hypotheses in the beginning of this chapter, and inner hand and outer hand limitation in problem identification in Chapter 1.2, proportionate steering motion is one of the main limit of steering wheel and its maneuvering methods. Now with this concept design that hand position can be

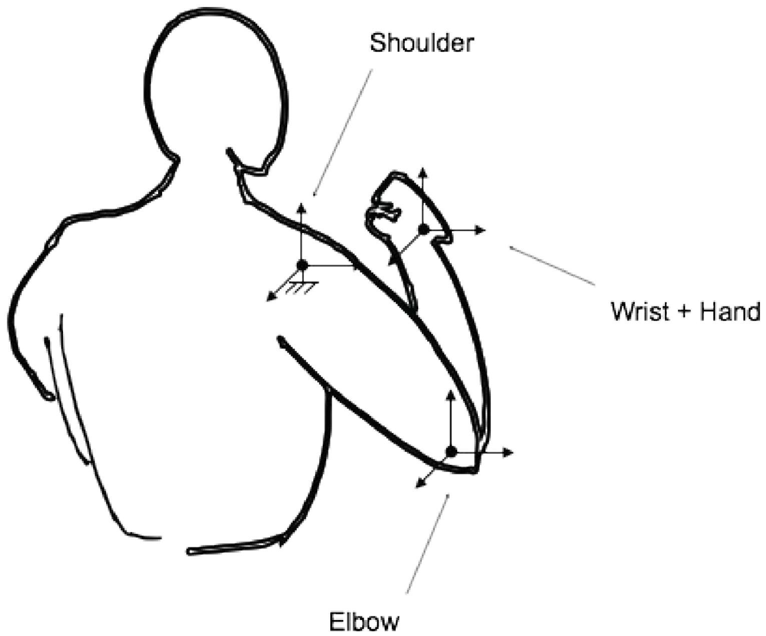


Figure 3.1: Upper limb motion anatomy

determined purely with vector rotation, disproportionate steering motion can be further extended to freedom in hand motion paths, which is the core feature of this concept design, 'disproportionate and non-circular-path-limited-steering-motion'.

As long as acquiring joint rotation information is possible, with above vector rotation operation and left and right hand position coordinates made available, steering output can be determined, regardless of possible error, such as in reality shoulder joints can hardly be a perfectly fixed point. The reason to this is that steering output can be viewed as definitive output generated from relative hand motion. This concept will be explained in experiment section, Chapter 4. Moreover, steering output can be determined with hand coordinate input, steering mechanism and algorithm can be further refined to optimize steering feel and effectiveness, depending on the level of adaptiveness desired.

With practically attainable tools, nor is acquiring hand coordinates a major challenge. Wearable device or exoskeleton style device comprising of measuring devices such as potentiometer or motion capturing camera can be designed or incorporated, and with these tools hand coordinates or motion information can be acquired either directly or converted indirectly.

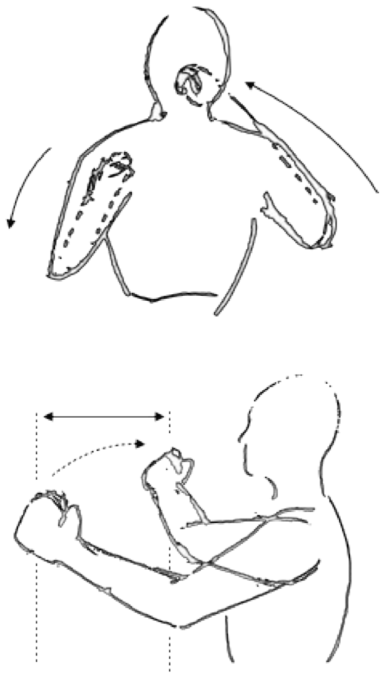


Figure 3.2: Side way views of steering motion. With inner hand and outer hand motion difference mentioned in Chapter 1.2 in mind, notice how steering motion can be redesigned to fit ergonomics more, while producing a more intuitive driving experience

3.2 Research Method

Before stepping into new concept realization, as two hypotheses were presented at the beginning of this chapter, we shall verify their validity first. This research adopts empirical method, since it would serve for easy observation, analysis and strong argument. In total two experiments were designed, set up and conducted. Due to limitation of timeframe and budget, both experiments were based on driving simulator, using the same driving simulation program on PC platform with game engine Unity. Detailed experiment setup will be explained in following chapter.

Chapter 4
Experiments & Results

PC driving simulator was adopted as experiment environment. The driving simulator, Edy's Vehicle Physics, was acquired through Unity Store. The simulator came with a simple city driving ground and a small off-road driving ground built in, and three passenger cars and a bus which the player can switch between. All vehicles included in-cockpit view to simulate realistic driving experience. Vehicle control in the driving simulator was originally through keyboard. Steering left and right were controlled by left and right arrow keys, pressing the arrow keys would continuously increase steering angle until reaching maximum: Steering angle gradients and fixed steering angle were virtually not available. This is contradictory to real driving scenarios where steering angle can be maintained at certain level by holding the steering wheel without further rotational input. To construct a desired steering mechanism, the driving simulator was revised and remapped to alternative input sources respectively in the two experiments.

4.1 Setup

4.1.1 Joystick Steering

As a preliminary experiment, a simplified steering wheel was conceived. In this experiment, the steering device was revised to two joystick-style handles, as demonstrated in Fig. 4.1. The two handles could be viewed as the hand-held portion of steering wheel, and it basically functioned in the same manner as steering wheel. Test subject steered by holding the handles and rotating it about an imaginary pivot axis. The fundamental difference of this setup with steering wheel was that test subject hands could act unrestricted as free bodies. Steering motion was not restricted to planar circular trajectories anymore, whether test subjects behaved differently or whether there were other behavioural traits could be observed.

Figure 4.1: Free body joystick style steering wheel handles

The silver-color balls attached to the joysticks are motion-tracking balls, these balls are a part of the motion tracking device used to record steering motion. To track hand motion, motion capturing device OptiTrack optical tracking camera V120:Trio was used. OptiTrack camera works by tracking special reflective tracking balls, which is the silver-colored balls attached to the joysticks. Minimally three balls are needed for the camera to determine a point in the space, more tracking balls provides higher accuracy. Due to space limit and camera vision limit, three tracking balls were used each handle. By simplifying the steering handles and test subject hands as mass points, the tracking points could be viewed as virtual hand representation, hand motion trajectories could thus be viewed as steering motion trajectories.

To elaborate the working mechanism of the joystick steering wheel, let's break down steering wheel visually and functionally, as interpreted in Fig. 4.2. Since initially the driver place his hands the steering wheel at 270° and 90° of the steering wheel, which is symmetrical, motion of rotating steering wheel can be regarded as rotating a 12 o'clock pointing vector. This is also intuitively applicable to driving within a range of steering wheel rotation, the more the steering wheel rotates, the more the front wheels rotate too. This logic can be intuitive and logically correct for one whole revolution of steering wheel, which would be leftward 180° and rightward 180°.

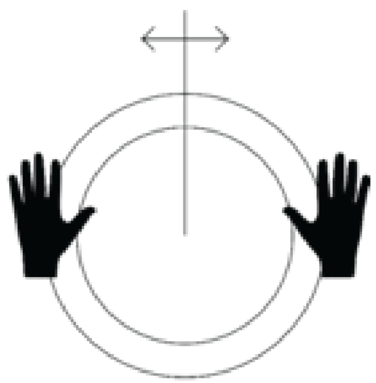


Figure 4.2: Simplification and visualization of user input to steering wheel

Practically, steering angle was calculated from tracked hand position. The tracking ball coordinates in three-dimensional space were first retrieved by the motion capturing camera. The coordinate input was sent to Unity by Local Area Network connection, the coordinates were then projected onto front plane, simplified to two-dimensional coordinates. Depth axis, which was z axis in Optitrack setup, did not contribute to steering input, only kept for later analysis on arm stretching and retracting motion. With every capturing instance a midpoint was averaged from left and right hand coordinates. By connecting the midpoint with Origin, a steering vector pointing from Origin to the midpoint can be formed. This is exactly the concept of rotating steering vector aforementioned in earlier paragraph. By calculating the angle between the steering vector and y axis unit vector, instant steering angle could be obtained. The calculated steering angle was further converted to a percentage figure, since in the driving simulator program lock-to-lock steering range was set as -1 to 1, 0 representing driving straight, while -1 and 1 represent full leftward steering and rightward steering respectively.

There are few things to be noted. The joystick is usually fixed to a base, and its rotational freedom is also limited, as evident in Chapter 2 discussion. In this experiment the joysticks can basically be considered as free bodies: it is capable of all pitch, yaw and roll motion, as well as free displacement in three-dimensional space. It thus differs from all past experiment and invention, and will serve as great source of observation, albeit its simplicity.

The other is that since the joysticks are free bodies and were held by human hands, the motion path will not be perfectly smooth and deviation is basically inevitable. This however will not affect steering input, since with the method adopted, a midpoint can always be averaged based on current left and right hand position, and the target of calculation is the angle of vector, inaccuracy and inconsistency of motion path thus are not of concern. Moreover, since midpoint is determined by left and right hand position, and in this experiment the steering wheel is comprised of separated free bodies, it further implies that even if left and right hands move disproportionately or asynchronously, instant midpoint, which determines steering vector and steering angle, can be calculated. This feature enables examination of the aforementioned hypothesis.

4.1.2 Decoupled Steering wheel

After preliminary experiment using free body joysticks, another steering device was designed based on the conditions in the hypotheses for further experiment, as shown in Fig. 4.3. The drawing was done using AUTODESK INVENTOR, and then 3D printed. The steering device had two separately pivoted but concentrically pivoted handles, one handle for each hand to hold. The steering device utilized the same concept of steering wheel, only that left and right input were decoupled in order to examine first hypothesis: Proportionate steering motion at respective hands. Test subjects were able to maneuver the steering device by holding the left and right handles and revolving the handles around their center pivot, only that left and right handles were not interconnected and were pivoted individually, 'decoupled', test subjects thus could have different rotational motion at two hands at the same time. The pivots of the steering handles were potentiometers, therefore when test subjects rotated the steering handles, it rotated the potentiometer knobs along. With electric power supplied the potentiometers would produce readings ranging from 0 to 1023 based on the amount of knob rotation, it thus served as a convenient tool for recording rotational input. The potentiometers were connected to the Arduino board attached at the back of the apparatus, which was further connected to the PC running driving simulator. The readings from the potentiometers were first pick up by Arduino Software, then sent to game engine Unity via serial port using a bridging script, and finally converted to steering angle in Unity. The following section will explain the conversion.

4.1.3 Steering Mechanism

The potentiometer readings from left steering handle and right steering handle were processed individually but identically. For the sake of comprehensibility, we will explain using left steering handle. The potentiometer reading when steering handle was held at initial position was considered as reference value. The amount of steering handle rotation, i.e. potentiometer knob rotation, can be converted as below:

$$LeftSteeringHandleRotation = \frac{(CurrentPotentiometerReading - ReferenceValue)}{1023} \times 300$$

300 is total travel of potentiometer knob, which is 300 degrees as indicated in technical specification. Left steering handle and Right steering handle angular displacement information were thus retrieved. To convert these two steering input into one final steering output, they were first converted by trigonometry to restore actual hand positions. The steering handle was pivoted by its 18 centimeter arm, therefore, again using left steering handle for comprehensive explanation, Left

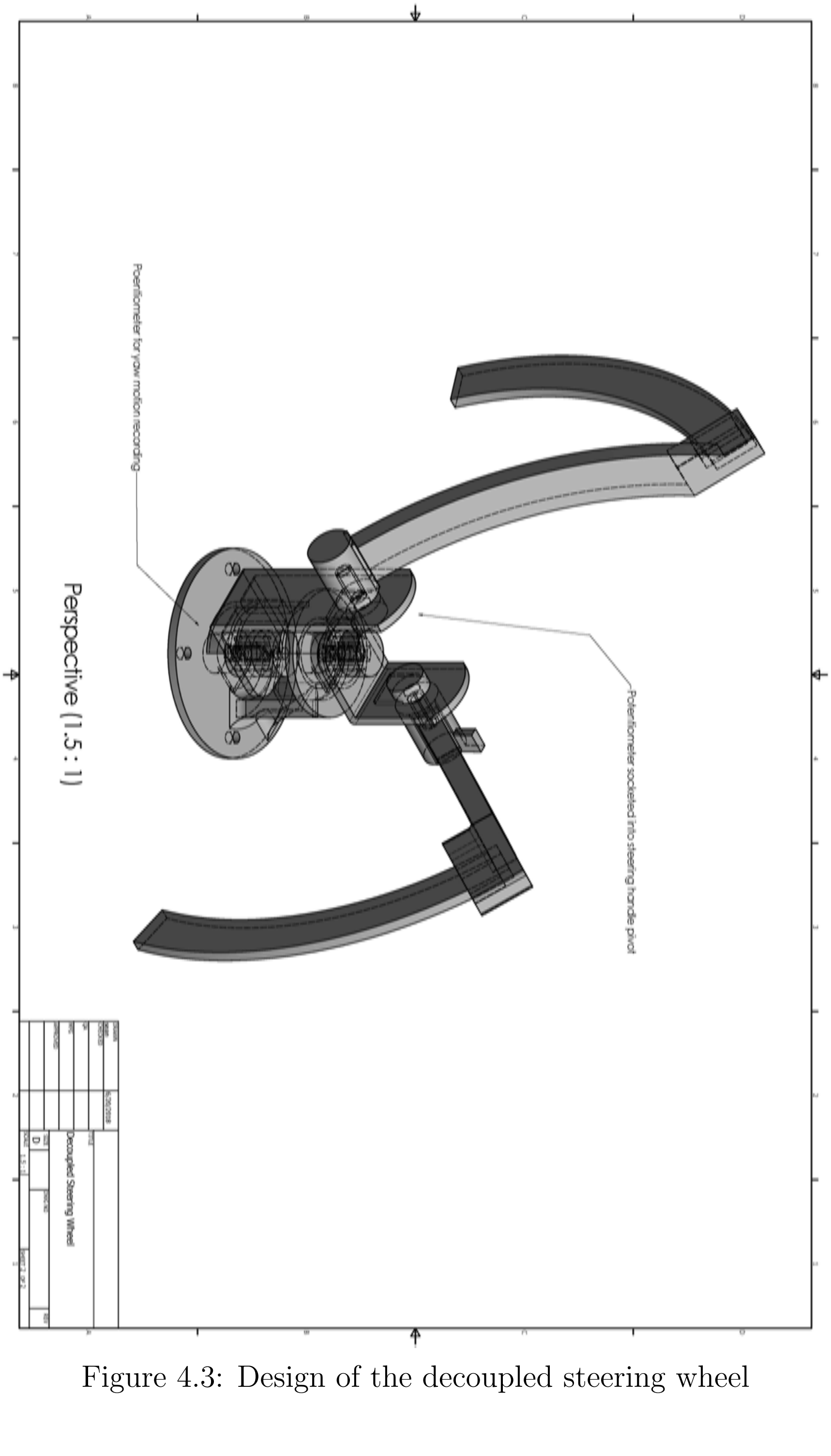


Figure 4.3: Design of the decoupled steering wheel

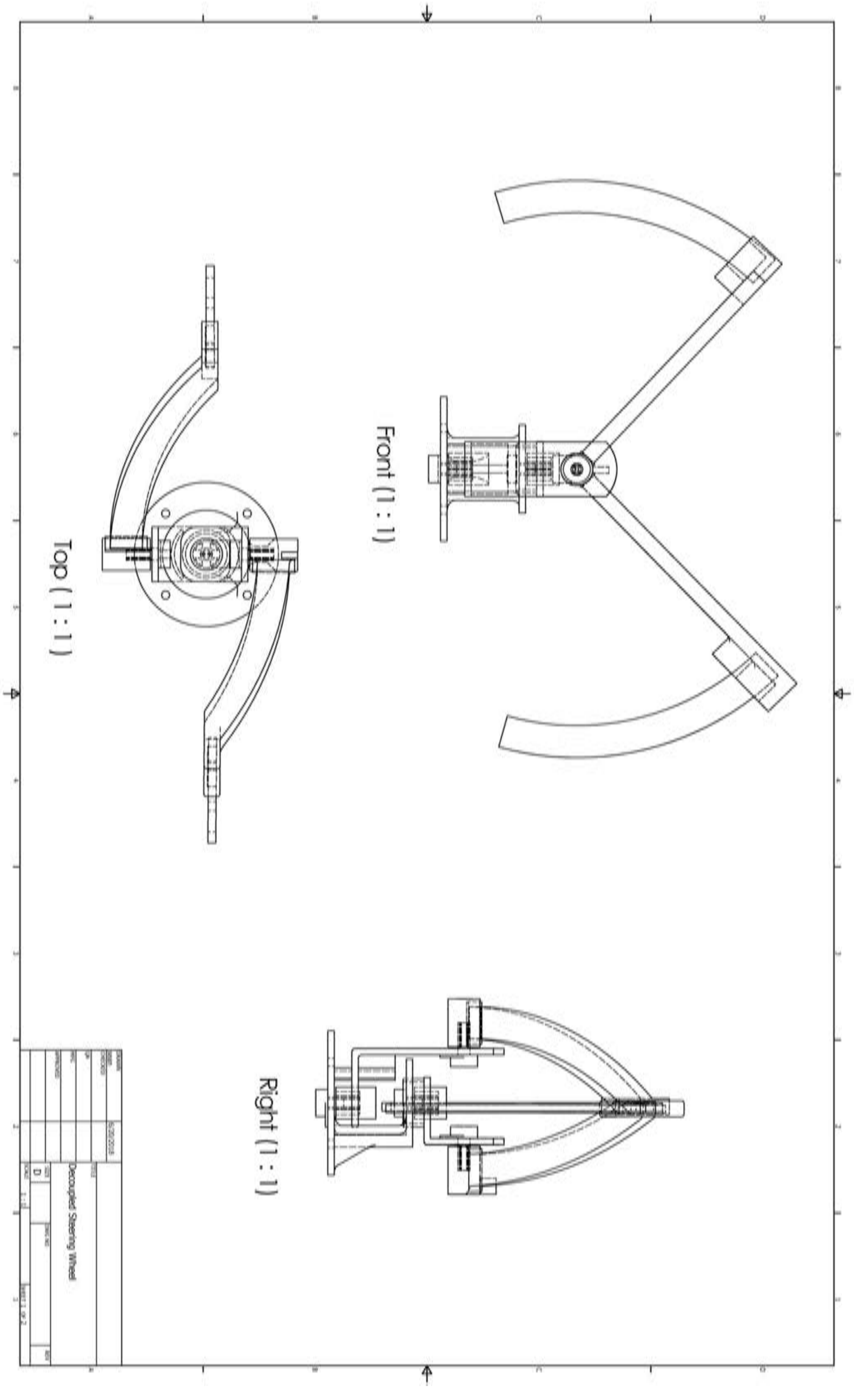


Figure 4.4: Orthogonal projection of the decoupled steering wheel

Steering Handle Rotation (LSHR) can be further converted by following formula:

$$LeftHandPositionOnImaginarySteeringWheel = (18 \times \cos LSHR, 18 \times \sin LSHR)$$

The product of above formula is a coordinate on two-dimensional Cartesian plane, representing the instant position of test subject left hand relative to time. Right hand position could be retrieved in the same manner. Now consider steering angle as the angle between y axis unit vector and the steering vector. The steering vector was determined by the midpoint of instant left hand and right hand coordinate and Origin. Let's first calculate midpoint:

$$Midpoint = (x_{LeftHandCoordinate} - x_{RightHandCoordinate}, y_{LeftHandCoordinate} - y_{RightHandCoordinate})$$

Steering Vector can be expressed as:

$$\overrightarrow{SteeringVector} = (x_{Midpoint}, y_{Midpoint})$$

It should be noted that steering vector was obtained by deducting Origin with Midpoint, according to definition of vector. Since Origin coordinate is (0,0), deducting any number by 0 does not affect the outcome value, it was simplified as above formula.

In the driving simulator the ultimate steering output was clamped between -1 to 1. The lower bound and upper bound represented left and right steering deadlocks respectively, and 0 would be interpreted as 0° steering angle, the range between 0 and lower and upper bound represented amount of steering. To acquire this number, the angle between steering vector and y axis unit vector was first calculated. It can be done mathematically, while in C# programming language Angle function taking two vectors as variable and returns the angle between the two vectors is available, the angle could be converted easily. The result was the steering angle. Finally, by dividing the steering angle with preset maximum steering angle, the [-1,1] steering output was acquired. This output would steer the virtual vehicle, same logic as with previous joystick steering device.

For this specifically designed steering device, the reason for determining steering angle output by simply averaging hand position is rationality and expediency. By taking midpoint of two hand coordinates, the steering device was able to function as typical automobile steering wheel when test subjects maneuvered

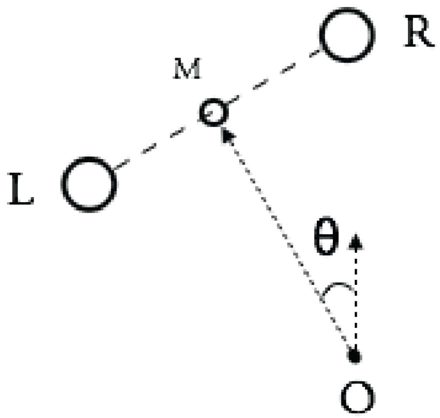


Figure 4.5: Midpoint and steering angle visualization. L and R represent left hand and right hand coordinates respectively, O represent Origin, M stands for midpoint, and θ is the angle between the steering vector generated by the hands and y axis unit vector.

the steering handles with proportionate and symmetric hand motion. When test subjects maneuvered the steering handle with disproportionately or asymmetrically, steering vector could still be determined and dynamically; despite how test subjects maneuvered the steering handle, a steering vector could be generated intuitively. Cases such as maneuvering the steering handles against common sense such that both hands moved toward each other and eventually collided was not in consideration, since test subjects were given brief of the steering device before experiment. Test subjects were explained that the steering device functioned the same way as typical automobile steering wheel, only that the steering device was decoupled and test subjects were capable of disproportionate hand motion. Test subject instruction will be explained in detail in latter section.

As can be seen in Fig. 4.6, the individual steering handle bracket was further pivoted to another potentiometer at its bottom, which was pivoted vertically. This pivot was designed for second hypothesis: test subject hands would not stay on the same plane during steering maneuver if given the freedom. The potentiomter served as a pivot and provided the yaw motion freedom, test subjects were able to rotate the steering handles about vertical axis. Data of this motion was retrieved with identical method to that of steering angle, only that it did not contribute to steering output, but restored for later analysis.

The shape of the steering handles was identical 60-degree, 18-centimeter radius

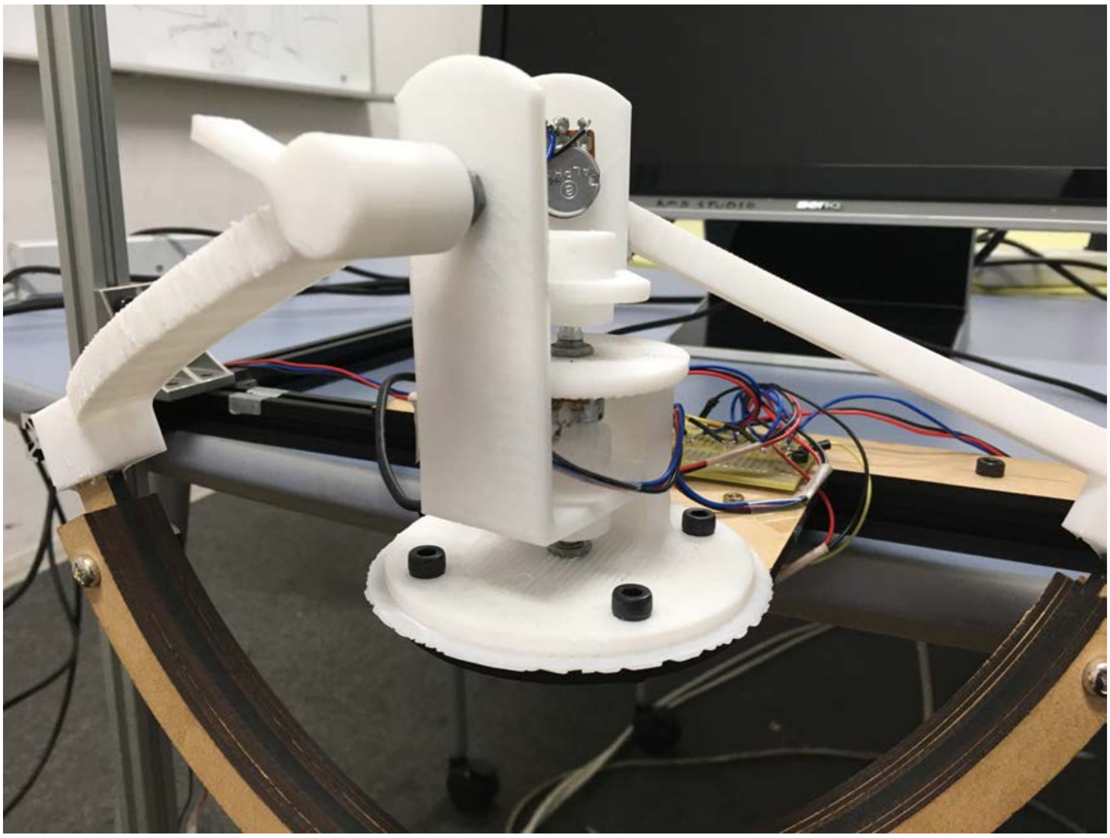


Figure 4.6: Closeup of the decoupled steering device. Notice the vertically pivoted potentiometers.

arc, and laser-cut from 3-millimeter and 5-millimeter plywood panels. Five pieces of 3mm plywood arcs were stacked and sandwiched by two pieces of 5mm plywood arcs, and then bolted together to serve as one steering handle.

4.1.4 Data Recording

With both experiments, as each instance steering motion was captured and converted to steering input, all the data from raw data such as hand coordinates, potentiometer rotation, to converted data such as steering vector, steering angle could be recorded for further analysis. Recording was done with built-in and common file I/O methods. Data were recorded in CSV format for the ease of further analysis.

4.1.5 Drive Force Input

In the original driving simulator setup, throttle and brake input were controlled by keyboard as well and were therefore binary; pressing the keys would only propel the vehicle at full thrust or decelerate at full brake. Realistic throttle and brake input were likewise achieved by using potentiometers as analog-to-digital converter. Throttle pedal and brake pedal units were designed using AUTODESK INVENTOR and 3D printed, drawing are illustrated by Fig. 4.7. The pedal was pivoted to a base. A simple suspension connected the pedal with the base. The suspension was a cylinder assembly attached with a spring, it could thus provide rebound force when the pedal was pressed. Potentiometer was fixed at the base, and the knob was capped with a rocker arm connecting to the pedal with a connecting rod. With this setup, when the pedal is pressed, it further compresses the spring on the piston. When pressing force is lifted, the spring rebounds and push back the pedal to initial position. As the pedal is pressed and rotates around its pivot, the connecting rod subsequently pushes the rocker arm and rotates the potentiometer. Conversion of drive input was conceptually the same as steering input, as shown below:

$$Acceleration/DecelerationInput = \frac{(CurrentPotentiometerReading - ReferenceValue)}{TotalTravel} \times C$$

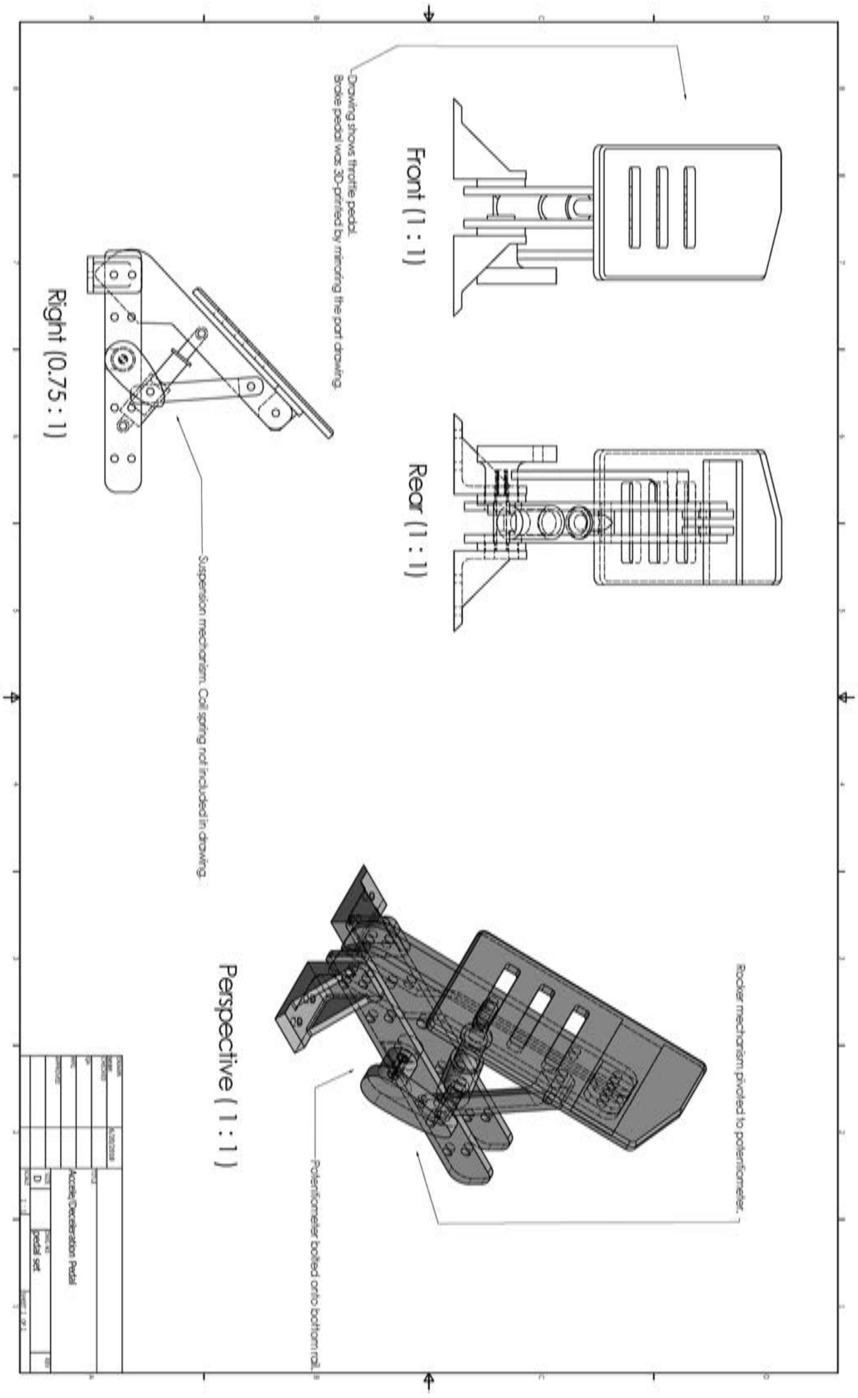


Figure 4.7: Engineering drawing of the throttle/brake pedal

Since the potentiometers were rotated by linkages and rockers, only a small portion of total available rotation would be used. Hence Total Travel is the degree of rotation by the cams. C was merely a coefficient for adjusting acceleration/deceleration level.

4.1.6 Driving Ground

The driving simulator came with a simple city layout and an enclosed off-road driving ground. In order to examine and compare test subject steering maneuver, the enclosed off-road course with various type of curves, including a long curve, a hairpin, a semicircle, an S-curve section, was chosen as the driving ground. The course layout and actual in-simulator view are shown in Fig. 4.8. The driving ground has same entrance and exits; the track eventually winds back to the entrance.

Figure 4.8: Layout of the full course

4.1.7 Experiment Procedures

The complete experiment apparatus was setup as demonstrated in Fig. 4.9 and Fig. 4.10 respectively. Steering device in Experiment One and drive pedals were mounted onto a custom frame, which was assembled from standard aluminum frames. The frame assembly was then fixed at desk edge using desk clamp. A laptop was used to run the driving simulator, and its screen served as monitor for the test subjects. For Experiment Two the decoupled steering wheel was disconnected and steering input switched to OptiTrack camera input.

Test subjects were informed the nature of the two experiments, and were informed the quest was to drive through the driving ground. They were also explained the devices they would be using. For Experiment One, test subjects were explained the steering device worked in same manner as typical steering wheel, only that it was capable of decoupled left- right hand steering motion, and the experiment did not judge based on the time taken finishing the course. No further explanation or hint was given. For Experiment Two test subjects were explained the steering handles served as left- and right handles of typical steering wheel, and it worked in same manner as typical steering wheel. Test subjects were informed the experiment did not judge based on how fast the drive course could be finished. No further hint or explanation were given.

In both experiments, test subject would do two runs. First run was for the subjects to try out the steering device, test-drive the virtual vehicle, and get to know the track. Second run was the formal run and steering data was recorded. The vehicle was placed in front of driving ground entrance, and test subject drove straight for a short distance before entering the driving ground. The experiment was conducted in Unity's editor mode, vehicle position could be reset by stop and replay the simulation. In the case when test subjects were stock, for instance few test subjects drove up the slope and were stock when corning at different locations, the run would be terminated and restarted.

4.2 Result

4.2.1 Joystick Steering

As a preliminary test, the joystick steering experiment showed very clear tendency. By plotting one of the test subjects' hand coordinates throughout the recording, the scatter plot gives clear picture of his over all steering motion trajectories, as illustrated in Fig. 4.11. The scatter plot plotted out the subject's hand coordinates throughout the course. Although not specified and therefore time series relation is not available, the scatter plot well presented the subject's steering motion tendency. From the available 3 test subjects' motion trajectories, although slight differences exist, for example some subjects' motion trajectories resembles

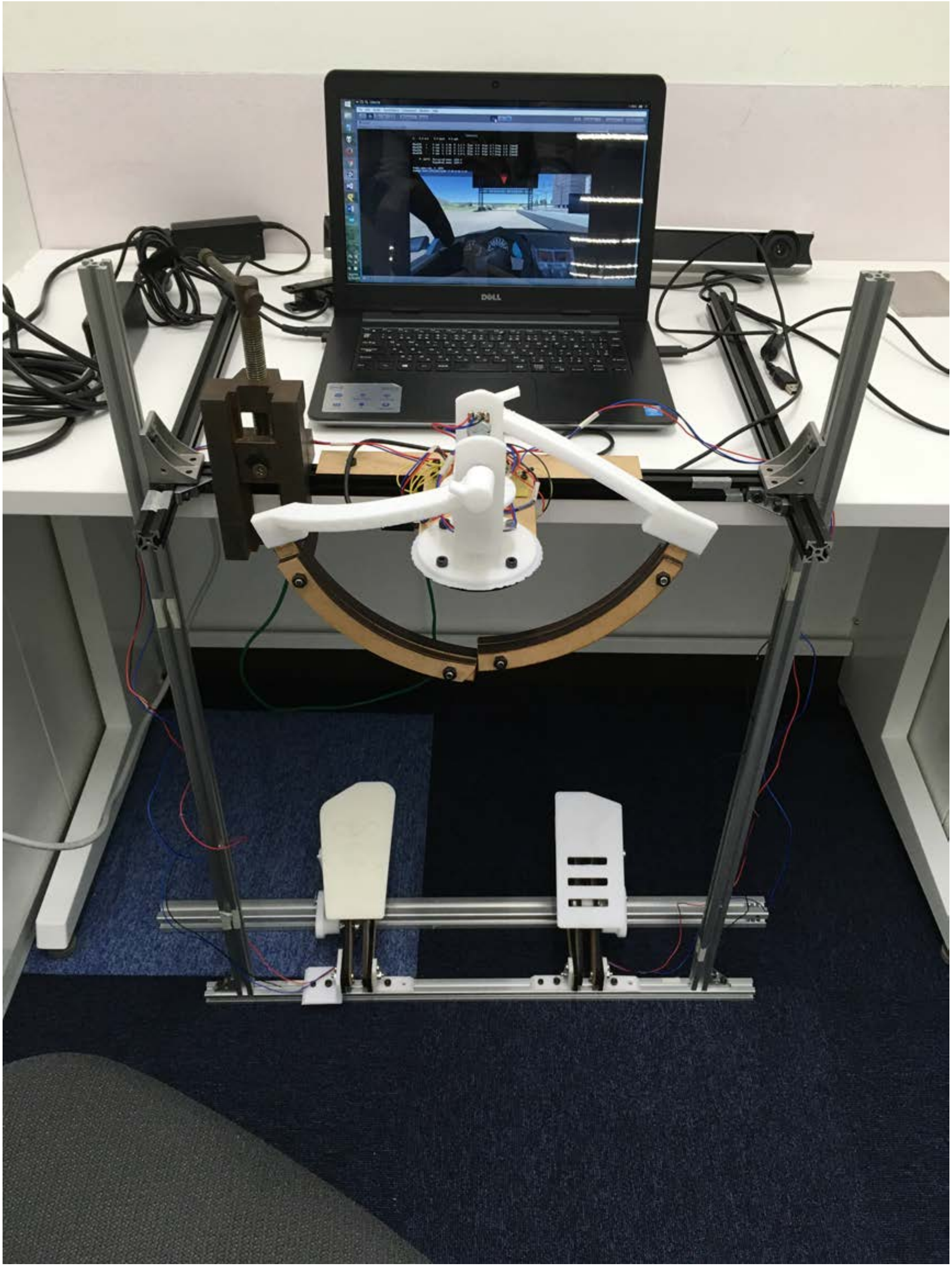


Figure 4.9: Complete setup of experiment apparatus with decoupled steering wheel

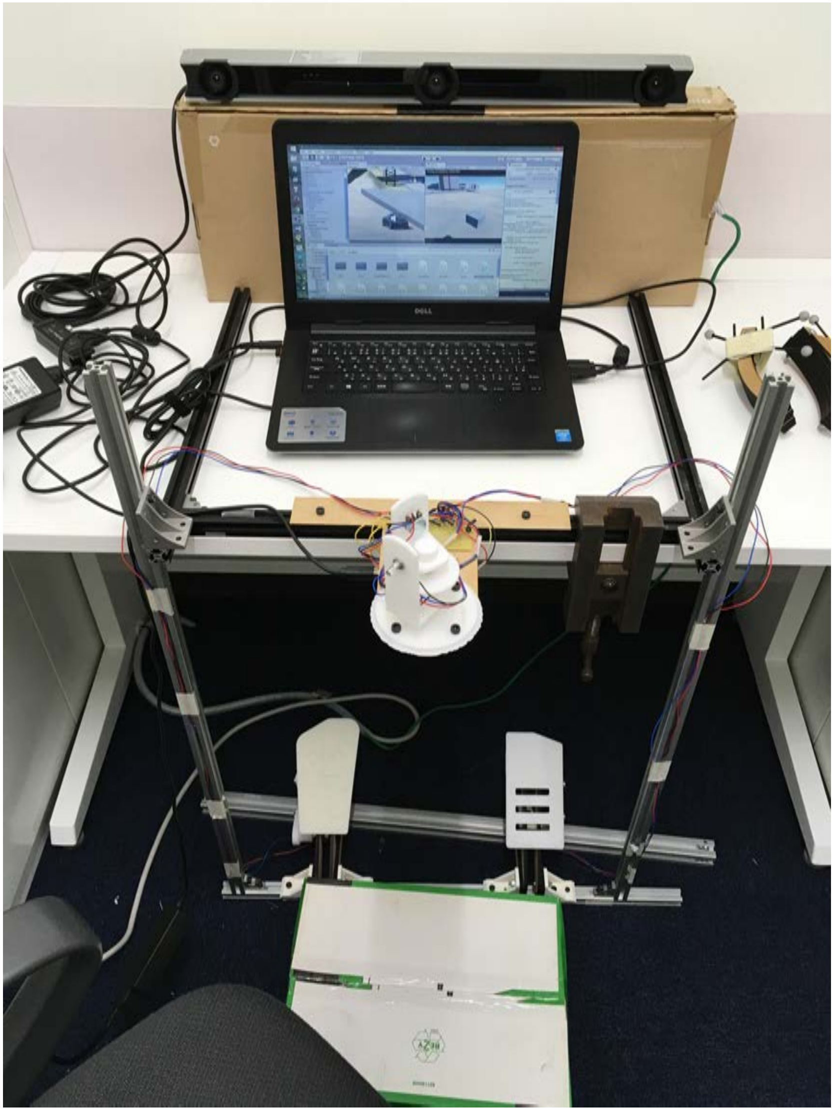


Figure 4.10: Complete setup of experiment apparatus with joysticks. Note the motion tracking camera placed at the back of the notebook PC, and the joysticks with tracking balls placed on the desk.

degree 2 polynomial, while others' shapes are almost circular, one common trait does exist: Despite the shape of test subjects' motion trajectories, upper end of test subjects' hand motion paths all extended longer. Relating this phenomenon to steering, it indicates that the test subjects did not move their hands downward as much as they moved their hands upward. To further interpret, it can be said that due to shoulder and wrist joint rotational limit, and with restrictions of typical steering wheel lifted, test subjects made use of the advantage of the joysticks and did not make counterintuitive arm joint motions.

Fig. 4.12 illustrates Subject 3's steering angle output throughout the course. In the figure, the section corresponding to second curve is marked in same color as in Fig. 4.13. Picking the color-striped section out and recovering it back to actual hand motion, another scatter plot can be reconstructed, as illustrated by Fig. 4.14. By approximation, consider left hand trajectory as straight line, total distance of left hand displacement is roughly 160 millimeters, while right hand displacement is roughly 200 millimeters. Since in this experiment the joysticks were free bodies, and there was virtually no base of reference, whether 40 millimeters of difference in displacement within one second is significant or not remains open to debate. What can be visually interpreted was that there was indeed difference among inner hand and outer hand trajectories.

4.2.2 Decoupled Steering Wheel

9 participated the experiment of decoupled steering wheel, with 8 finishing and produced analyzable data. For the ease of explanation, subject 4 will be used to elaborate the key comparing points, and comparison between the eight subjects will be shown later. The total run time of subject 4 was 47 seconds, steering angle throughout the run with respect to time is demonstrated in Fig. 4.15.

To examine in detail, we shall further look into the subject's motion during specific curve. To provide better clarity, Fig. 4.15 was further divided into sections correspondingly to demonstrate steering wheel angular displacement at different corners in the driving ground, indicated by color strips. The color strips correspond to Fig. 4.13 by color and number. In the steering angle graph y axis represents steering angle, and its Origin divided the graph in half vertically, with the value increasing positively upward and negatively downward. y axis Origin represents 0° steering angle, which is straightforward travel direction. Positive steering angle represents clockwise steering wheel rotation, while negative represents counterclockwise steering wheel rotation, as illustrated in Fig. 4.16. It

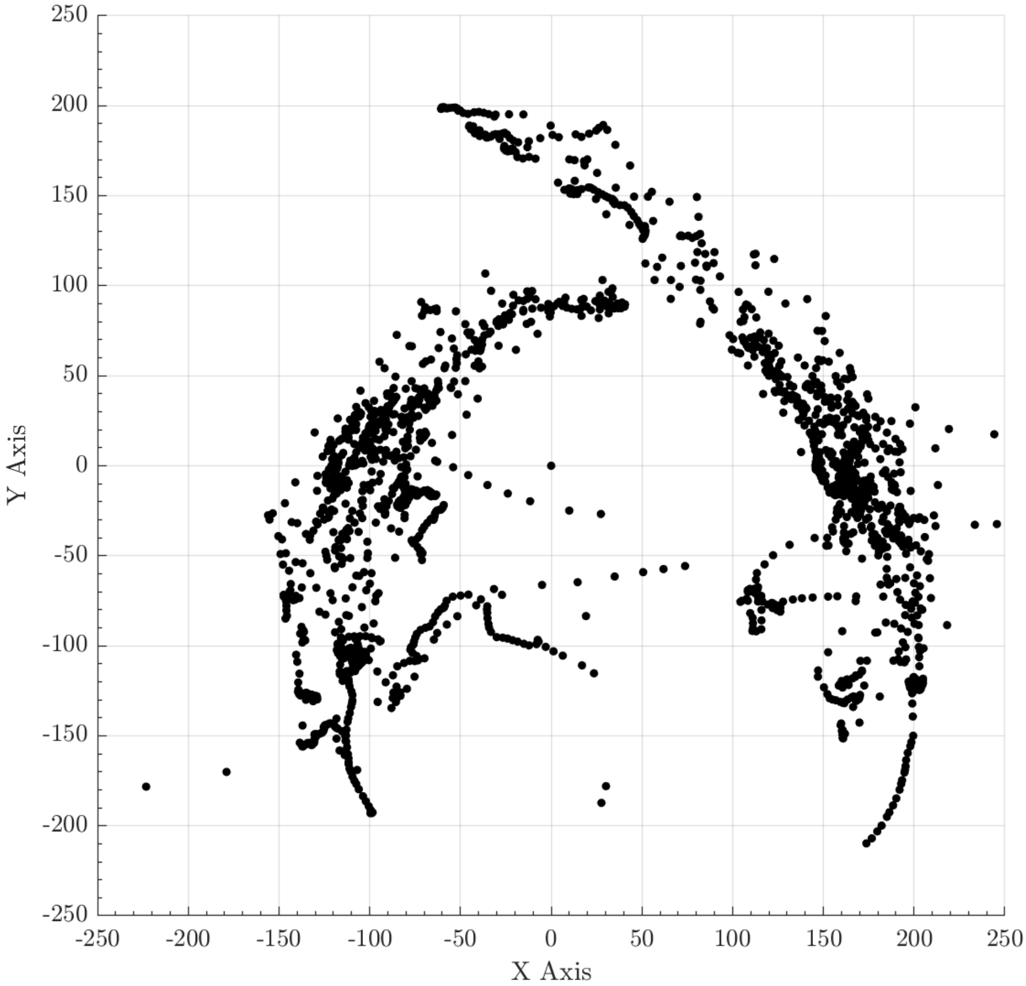


Figure 4.11: Scatter plot of Subject 3's steering motion throughout the course. Hand motion trajectory tendency can be clearly observed visually.

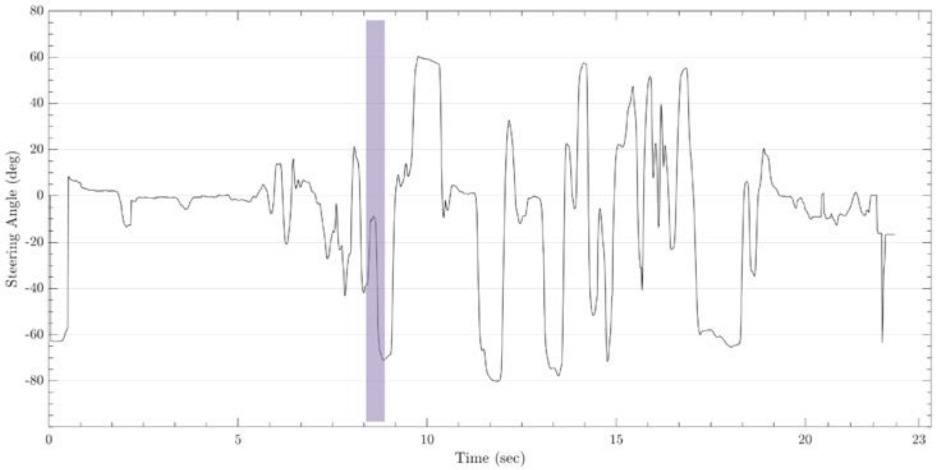


Figure 4.12: Subject 3's steering angle throughout the course. color-striped section indicates subject's steering angle output in second curve.

should be noted again that here steering angle refers to angular displacement of the steering wheel, not the final output steering angle, as addressed at y axis title in the graph.

Same as with joystick steering experiment, the corners in the driving ground are correspondingly marked with same colors to that in the steering angle graph, as illustrated in Fig. 4.13. First curve is a long left-hand curve, more an introduction into the course. Then there comes another further left-hand curve, and followed by a right-hand hairpin curve. After a mid-length straight there are two identical left-hand curves, and the second left-hand curve leads to a series of S-curves, which is the final section. Curve 2 and Curve 3 are chosen for further analysis for few reasons. First, since that the two curves are of opposite direction, they make for clear distinction in the data plot and convenient comparison with actual driving ground. Second, the nature of the curves, one being a 90° turn and the other a 180° turn, helps demonstrate few crucial steering behavior that is the target of observation for this research, including steering angle difference and hand position change.

To analyze the test subject's steering maneuver while cornering, we shall take advantage of the decoupled steering wheel design, and look at the test subject's input fluctuation of individual hands during steering maneuver. To achieve this, two data series need to be reconstructed: supposed hand angular position on an

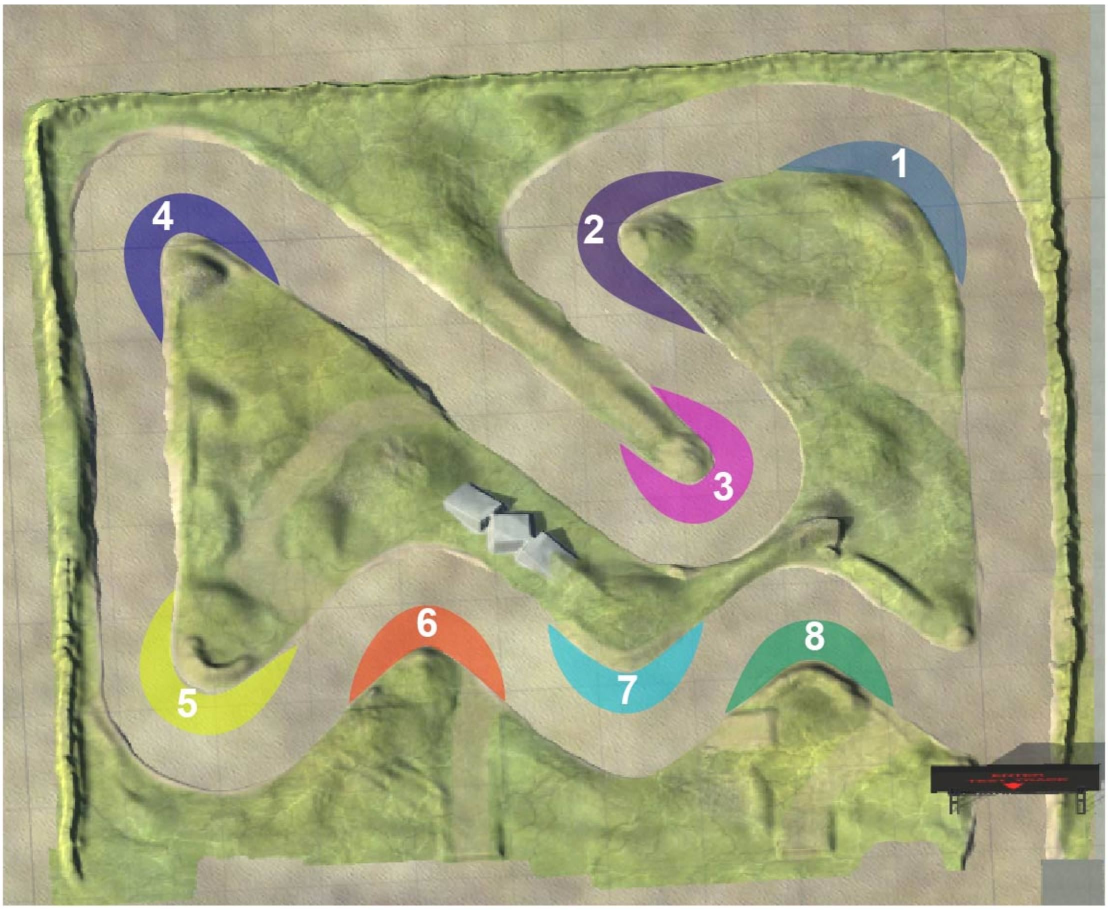


Figure 4.13: The corners in the driving ground are marked in colors corresponding to steering angle graph.

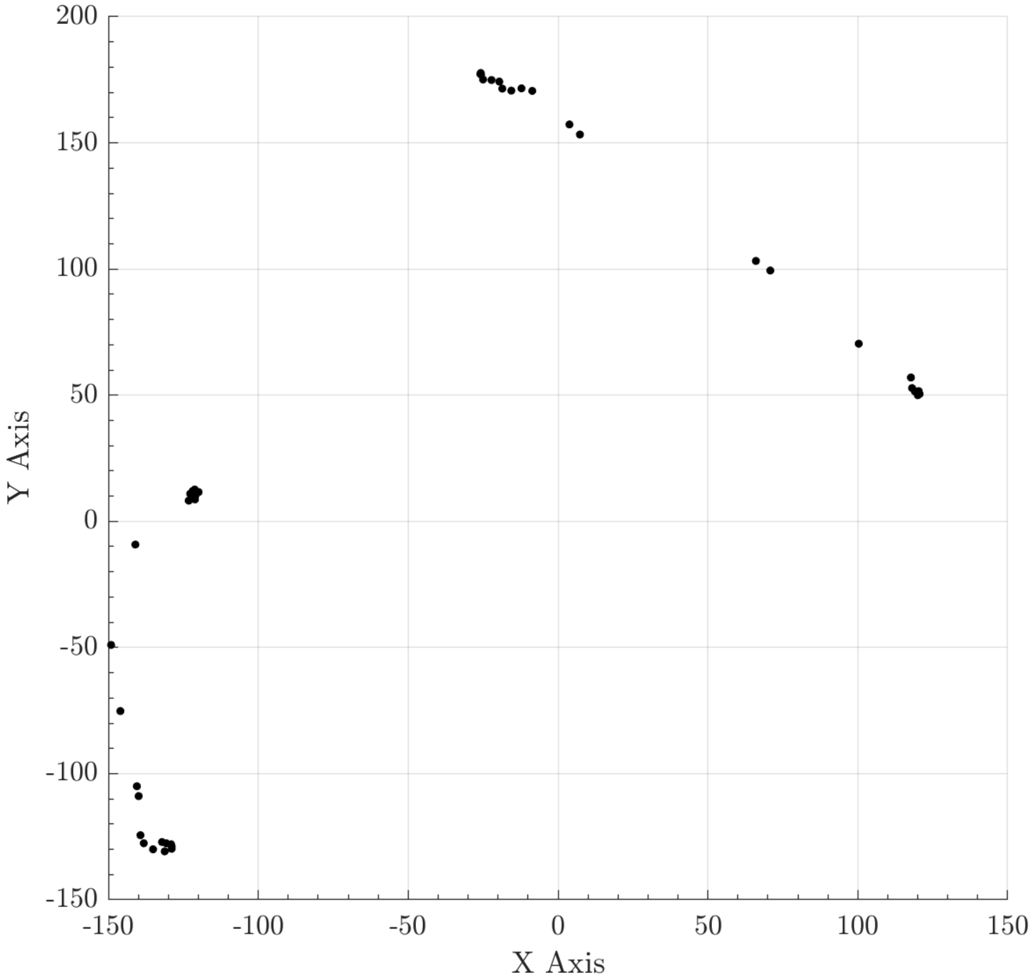


Figure 4.14: Subject 3's hand motion trajectory in second curve

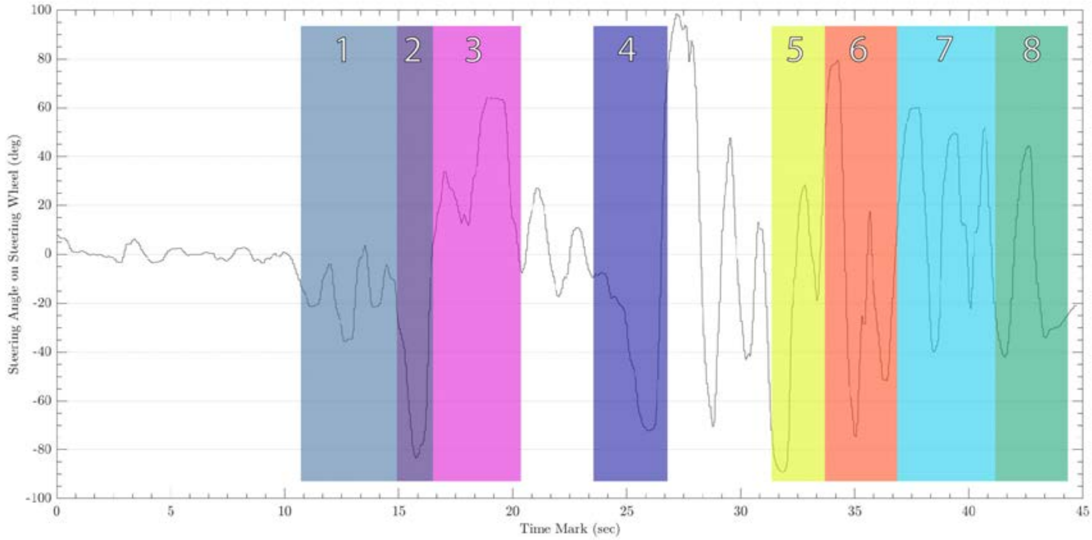


Figure 4.15: Test subject 4's steering angle output with respect to time

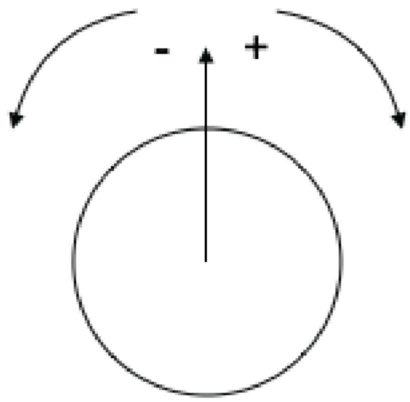


Figure 4.16: Polarity setting of steering angle in the experiment

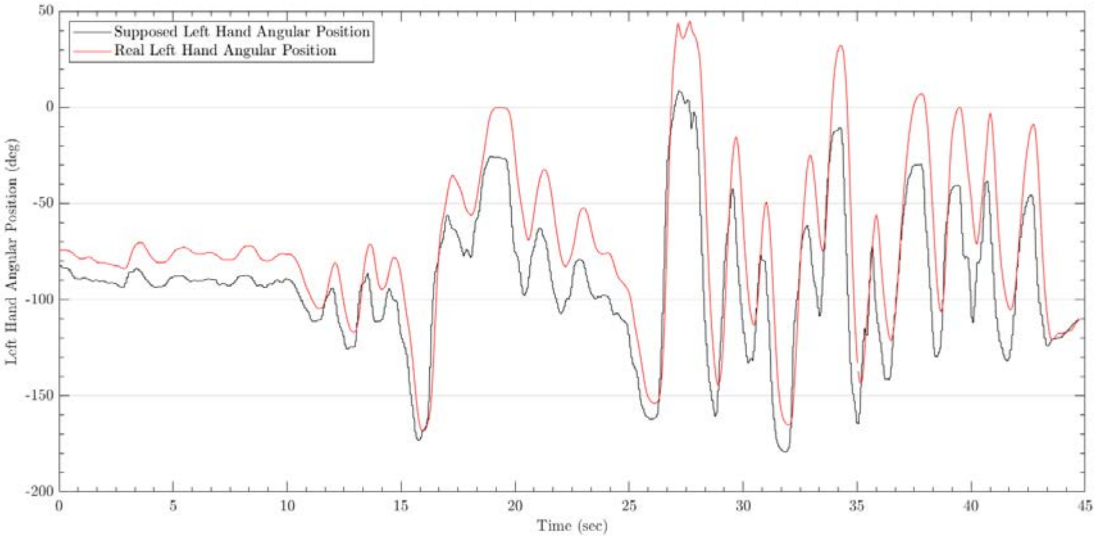
imaginary steering wheel, and actual hand angular position of the decoupled steering wheel. 'Supposed hand angular position' refers to the assumption that the test subject's steering angle output was from a typical steering wheel. Let's consider an imaginary typical steering wheel, as illustrated in Fig. Steering wheel rotation can be considered as the amount of angular displacement of an imaginary steering vector pointing to 12 o'clock. Assuming the test subject was using the steering wheel, and he held the steering wheel at 9 o'clock and 3 o'clock. With steering vector rotation data available, left and right hand angular position throughout the drive can be reconstructed as well. This can be done using rotation matrix:

$$\begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix}$$

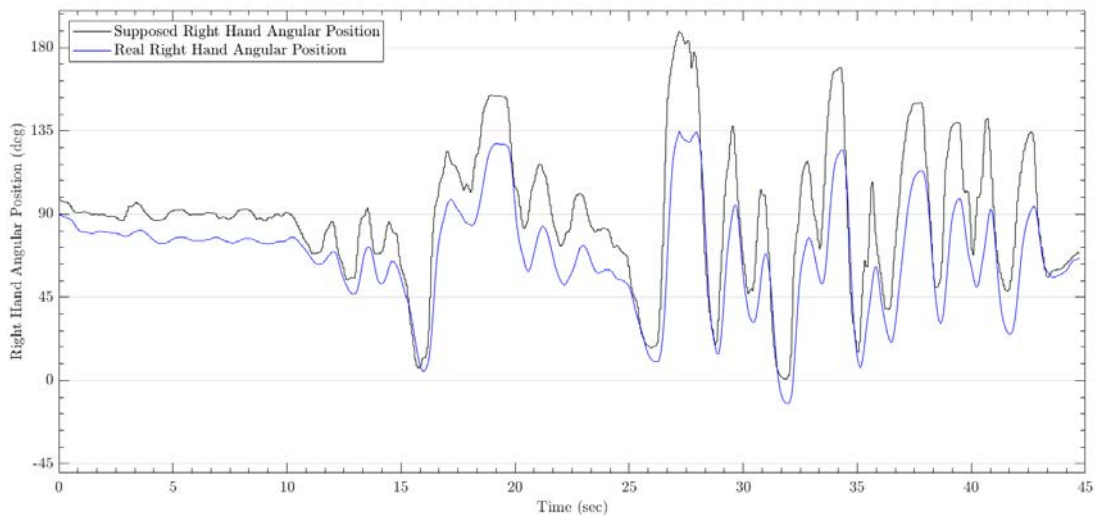
Same conversion can be achieved by adding/subtracting 90 to the steering vector angle, but such manipulation would require extra steps of correction, due to different Origin to that of Euclidean space; steering vector Origin was set as Euclidean space y axis unit vector (0,1). The derived left and right hand angle would be 'hand angular position on the imaginary steering wheel'. Although in the experiment the steering device was the decoupled steering wheel, with such assumption, supposed hand angular position on a typical steering wheel can be constructed.

Real hand angular position with the decoupled steering wheel can be converted in similar manner. As explained in Chapter 4.1.2, left and right hand rotational motion was recorded in the form of potentiometer knob rotation, and that the length of steering handle arm was 18 centimeters. With these data, instant hand coordinates in three-dimensional space can be reconstructed precisely. Trigonometry arctangent function alone was enough to convert hand coordinates to angles relevant to steering vector. Extra steps were made to correct error resulting from different Origin issue and Euclidean space quadrant. Finally, by plotting above two data series, significance of hand motion fluctuation can thus be observed, as demonstrated in Fig. 4.17.

Due to the setting that steering vector was determined by averaging two hand coordinates, error would exist. The beginning section of the driving ground was a long straight line, with a typical steering wheel hand angular position should be very close to 270° and 90°, but it can be observed that in the graph at the corresponding section there is a constant deviation of roughly 10 degrees. This implies that the test subject's hands were not at the absolute correct angular position to produce 0° steering angle. Since the decoupled steering wheel was designed to allow fluctuation in steering maneuver, with any given steering vector angle,



(a) Left hand angular position comparison



(b) Right hand angular position comparison

Figure 4.17: Actual hand angular position as compared to supposed hand angular position on a typical steering wheel

the decoupled steering wheel allows infinite combination of hand angular position from the test subject's two hands; that is to say, the test subject's hands could be at different positions for a same steering angle at different timing. However it is not this error but the fluctuation of the hand motion that is the target of observation. It is not the absolute position of the hands, but the angular displacement over time that we are targeting. The 'error', or put in a different way, 'designed flexibility', is what enables motion fluctuation to be observed.

By looking at left and right hand angular position curves demonstrated in Fig. 4.17, it is visually apparent that in almost all curving steering maneuver, considerable hand motion fluctuation exists. Moreover, disproportionate steering motion does exist. In third curve, which is a right-hand hairpin curve, it can be visually interpreted from Fig 4.17 that the test subject's inner hand, which is his right hand, steered more than supposed amount of steering, and his outer hand, left hand, steered less. It can also be observed visually from the graph that effective range perceived by the test subject roughly covers 220 degrees for left hand and 130 degrees for right hand.

To examine the fluctuation analytically, let us look at the test subject's hand angular displacement when entering second curve and until reaching maximum steering angle in the curve. The section representing the subject's steering angle output in second curve is indicated in Fig. 4.15 with number 2 and color stripe. For the sake of comprehensibility let us use left hand for elaboration. First the data range corresponding to this section was extracted. First data entry of the extracted data entries was set as reference, and all of the rest data entries subtracted this reference value. By this calculation, amount of left hand angular displacement of each capturing instance was acquired. Same data manipulation was applied to right hand data. Finally the two data series were plotted as in Fig. 4.18, the respective curve represents accumulated hand angular displacement over time. It is clear that as time increases, instant slope of left hand curve become steeper, which represents that for the same amount of time left hand angular displacement was more significant compared to right hand. Since second curve is a left-hand curve, with the case of test subject 4, practically the data implies that subject 4's inner hand steers more than outer hand, which is rather counter-intuitive and opposite to the hypothesis proposed earlier. To compare whether this is consistent with all test subjects, we can apply same process to derive steering motion of the relevant section of the seven subjects whose data were complete and correct, the result is demonstrated in Table 4.1. In the table, hand angular displacement

	Slope		Angular Displacement		
	Left	Right	Left	Right	Δ
Subject 2	-2.5	-2.8	70.13	69.90	-0.23
Subject 4	-1.5	-0.88	57.64	89.56	31.91
Subject 5	-1.6	-0.83	45.29	28.86	-16.43
Subject 6	-0.68	-0.78	76.59	76.21	-0.38
Subject 7	-0.45	-0.22	33.18	16.67	-16.51
Subject 8	-0.92	-0.74	63.95	48.63	-15.32
Subject 9	-1.8	-1.9	77.14	71.80	-5.34

Table 4.1: Second curve steering motion of the 8 subjects

over time was demonstrated as slope, which was derived by linearly fitting the hand angular displacement curve. Although according to strict definition, linear regression does not apply to analyzing the data here, mathematically it is still valid for acquiring the line with minimum square error. Again, error is not the key issue here, but general trend is what this research intends to identify.

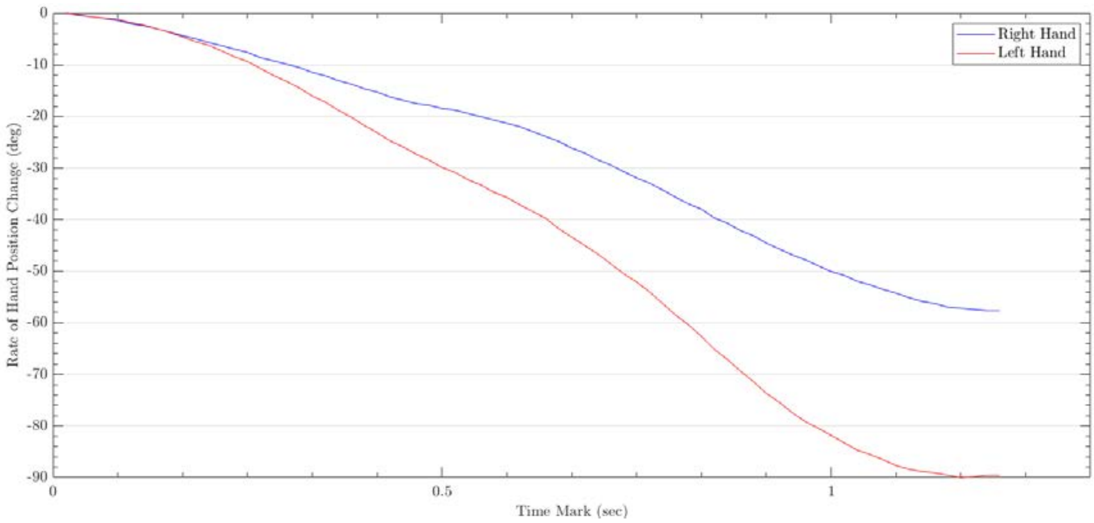
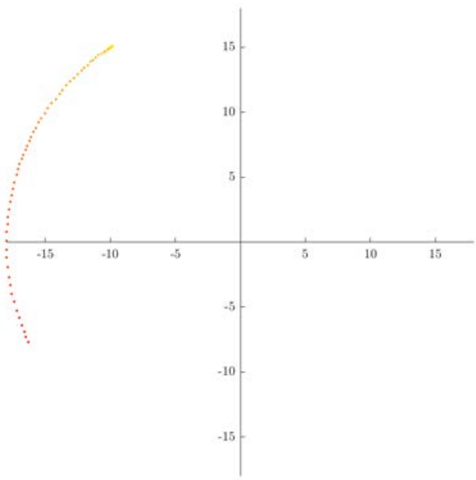


Figure 4.18: Subject 4's hand angular displacement over time upon entering second curve

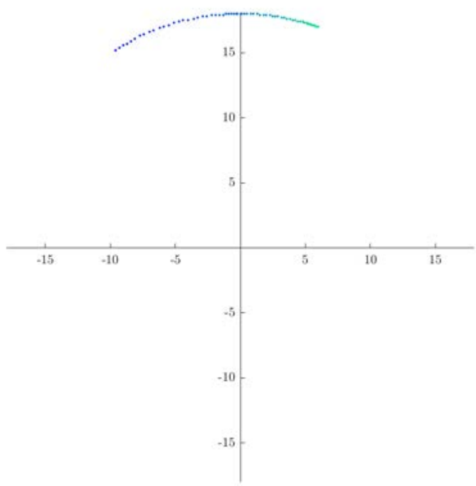
In Table 4.1, column Δ represents the difference between left and right hand angular displacement. With the case of second curve, which is a left-hand curve, positive delta implies outer hand displaced more than inner hand, while negative delta means inner hand displaced more than outer hand. As discussed in Chapter 1.2, by ergonomics inner hand should displace less than outer hand. While from this particular curve in this experiment, three of the eight Subjects demonstrated significantly bigger inner hand angular displacement. However Subject 4 does exhibit larger outer hand angular displacement, and more significant than the previous three Subjects in terms of angle.

To present hand angular displacement visually, hand position data can be used to plot actual hand trajectories, as illustrated in Fig. 4.19. Comparing to Fig. 4.17, with scatter plot, color gradient and Euclidean plane, the test subject's total hand displacement range can be more easily understood. For Fig. 4.19(a), first entry of left hand position is marked as yellow, color gradient represents order of time, the last entry is the coordinate with deepest red. Hand fluctuation can happen during steering motion, in the graph it would result in overlapped coordinates, which undermines readability. By cross-referencing with Fig. 4.18, in the case of Subject 4, fluctuation is absent.

With other subjects, different and somewhat interesting behavior was found. For instance, with Subject 9, real hand steering motion deviation from the supposed curves was stable, which implies that Subject 9's steering motion was very close to actual steering motion using typical steering wheel.



(a) Left trajectory throughout extracted section



(b) Right trajectory throughout extracted section

Figure 4.19: Test subject 4's hand trajectories when turning into second curve

Chapter 5
Conclusion

5.1 Concept Design - A Sample

In Chapter 3, concept design which overcomes identified limitation was proposed. Although the conceived mechanism is viable, actual implementation would raise few more technical challenge. As elaborated in Chapter 3, the steering motion contributors and conversion mechanism for the new steering method have been identified, discussed, and how to retrieve hand motion information for steering input has also been solved, the remaining work would rather be on deciding what mediums works best and is most reliable, and how to improve overall packaging in real cockpit. A first challenge this research would like to look upon is driver arm fatigue. One of the important merit of steering wheel is that it provides leveraging points for the hands, as explained in Chapter 1.2, and it consequently limits arm fatigue. However with this new steering mechanism proposal and the steering wheel removed, now the challenge lies in supporting driver's upper limbs, and provide necessary level of force feedback. In this first design draft, as demonstrated in Fig. 5.1, gas springs were used to achieve the desired effect.

The arm supports serve for two important functions, one being solving arm fatigue issue, the other being guiding the driver on steering motion. The arm supports were designed to be leverage points for the driver's arms and the rebound force from the gas springs. The gas spring was pivoted in such a way that when the driver's arm rests at straight forward, non-curving steering posture, it is compressed but not fully compressed, and the rebound force equals to gravity pulling the upper limb towards earth. With this setup, it was assumed that the forearm forms roughly 90° to the arm, and forearm is also balanced so that it does not cause fatigue. Detailed close-ups are shown in Fig. 5.2.

The forearm part was designed as the extension linkage for the steering joysticks. The forearm linkages were pivoted to arm support with planar rotation freedom, which resembles real elbow joint. Its other end, which would reach the

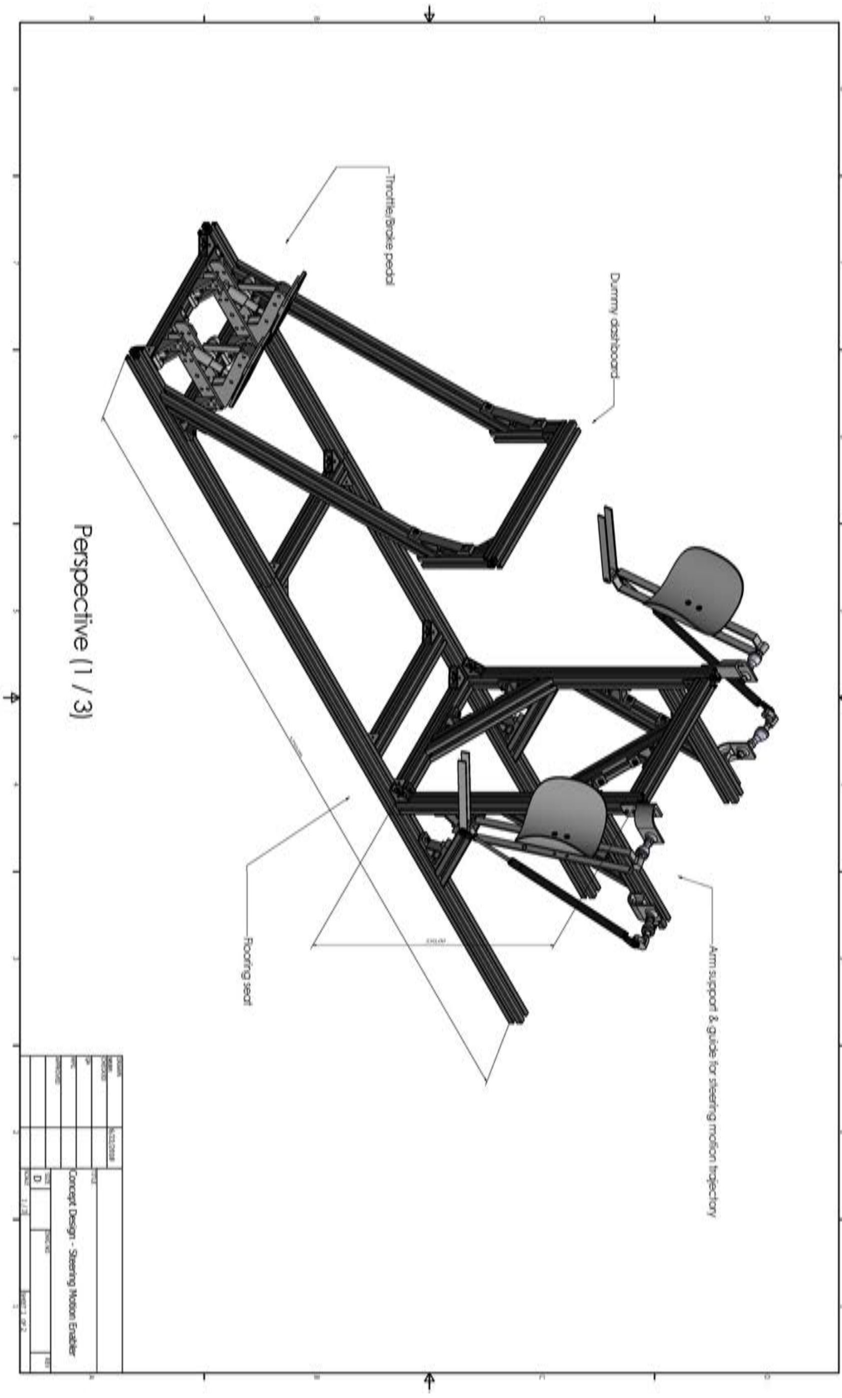


Figure 5.1: Concept design - the external cockpit. Key point of the design is the arm support mechanism

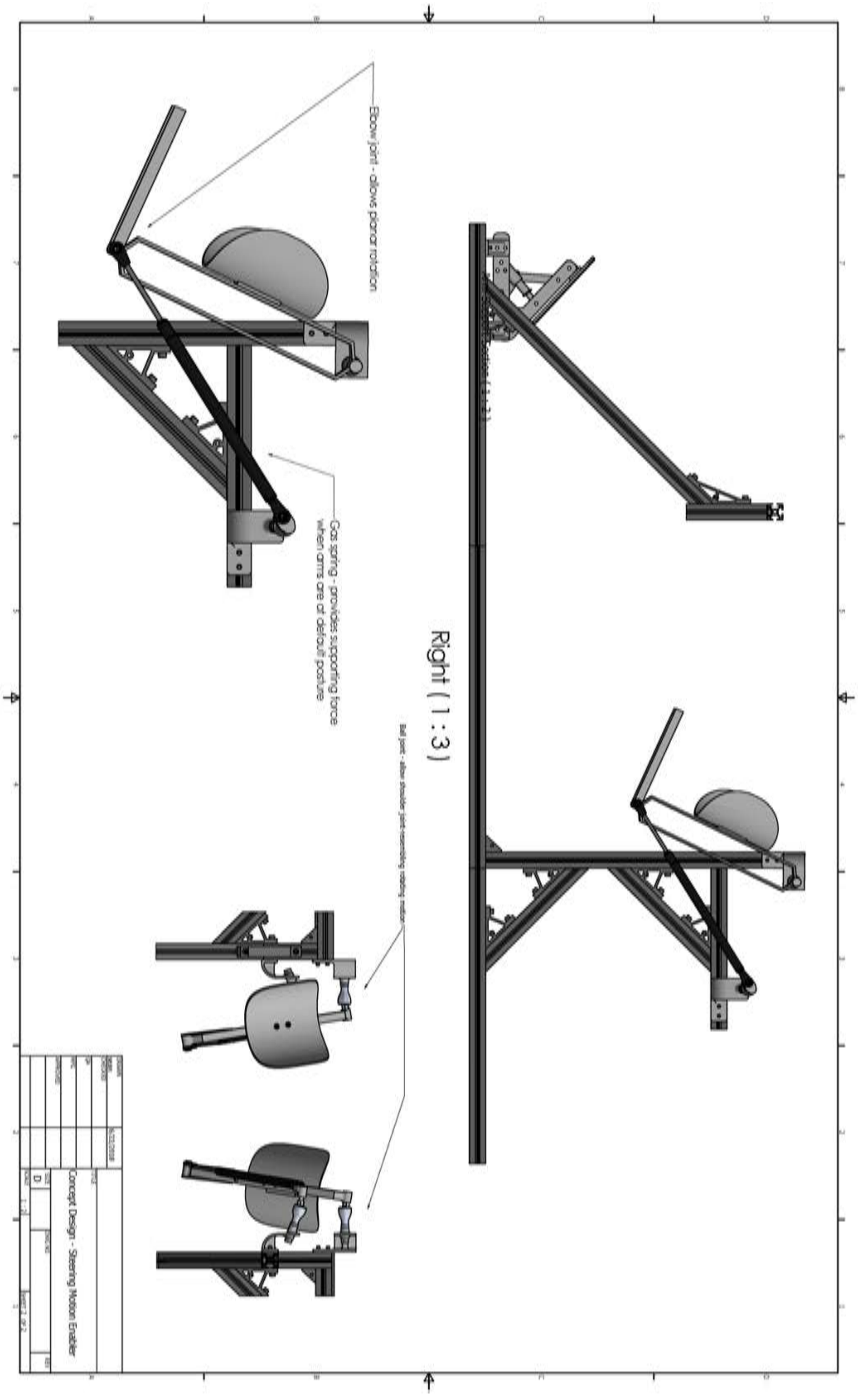


Figure 5.2: Concept design - the design of arm support.

driver's wrist, was simply meant for connecting the joystick. Whether the connection with joystick should be full 3 degrees of freedom joint, or just limited to certain axial rotation, is open to debate and might require further user study to determine, for simplicity it is set as only one axial rotation freedom, since earlier studies [19] also identified steering motion to be relevant with arm muscle, not with wrist rotation.

The upper limb support assembly was pivoted to the frame with two ball joints. One is at the gas spring, the other at shoulder position of the arm support part. Additionally, the gas spring is capable of changing length by applying/lifting compression force. The upper limb assembly thus provides the freedom of unconstrained movement within effective range of Hand-over-Hand Steering. It can simply be considered an exoskeleton for the driver's arms with force feedback physical weight support function. The driver steers by holding the joysticks and maneuver it as substitute of steering wheel, only that the driver is not limited to circular planar motion anymore.

As an initial design draft, gas spring serves as an average solution for solving driver arm fatigue. As a whole how arm fatigue solution can be integrated with the core invention, which is the new steering mechanism elaborated in Chapter 3, considering practical issues including packaging and safety, requires more design iteration and remains the work for further development.

5.2 Impact for Society

Autonomous Vehicle and Intelligent Vehicle has received much attention in the past two years, especially after both semiconductor and software industries came into play to provide various in-vehicle solutions, and some major manufacturers started taking formal business moves to transition from pure makers towards also as service providers [3]. In such context, attention and actual development efforts have been focusing on refining autonomous driving technology. Regarding steering wheel, practical solutions proposed by automakers and key suppliers only went as far as repackaging steering wheel to create usable space for the driver and front row passenger. Aside from the concept car proposals and individual experiments as mentioned in Chapter 2, no published work has really looked into driver side steering mechanism. Utmost effort stops at adding various levels of ADAS functions and repackaging [14].

In the most demanding arena of automobile, auto racing, to reach maximum efficiency in terms of response time and control accuracy, steering ratio can be adjusted accordingly [7], thus redundant motion is greatly reduced. For professional motor sports, it is not uncommon the steering wheels are adjusted to have only 90° steering range for leftward and rightward rotation respectively. Despite the steering ratio being adjustable, it still did not fundamentally solve the issue of ergonomics, which could be a contributing factor for driver performance, as claimed and proofed by Tajima et al. [19]. On the other hand with concept cars, NISSAN positioned intelligent steering wheel as one of the main feature on its IDS concept [14], particularly driving pleasure was mentioned as co-existent with its autonomous driving capability. Still, the steering wheel design essentially did not change. Despite its form or function, its mechanism remained the same as typical steering wheel, a centrally pivoted rim.

As explained in Chapter 3, the concept design proposed by this research eliminated driver-facing, dashboard mounted steering wheel. Albeit the new design hardly reached A Sample stage, it brought up the possibility and feasibility of side-mounted or rear-mounted steering device. With further development, how much can it either stay as a purely greatly refined steering system for driving pleasure, or integrate with autonomous driving to bring the driver a good mixture and balance between enjoying road trip and enjoying driving the vehicle? It will be the future work towards B, C, D Sample and actual implementation.

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