Motion Planning by a Two-Degree-of-Freedom Driving Simulator for Optimal Generation of Acceleration Sensation

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Abstract

This research focuses on inducing the perception of acceleration in the occupant in accordance with a given motion for the vehicle. For a desired driving experience without using a high-degree-of-freedom and expensive mechanism, without the actual presence of the occupant in the moving vehicle, the presence of the occupant in a two-degree-of-freedom simulator creates the perception of being in that motion. Human perception of motion is created through the measurement of various physical parameters, primarily vision, acceleration, and sound, and by different receivers. This research targets only the vestibular acceleration sensor, as the most important acceleration sensor in the human body, to induce the desired sensation and, due to the lower degrees of freedom of the mechanism compared to the actual motion, the simulator motion in the presence of various limitations is optimally planned and discussed based on the closest motion sensation to the desired motion in two horizontal and vertical directions.
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Keywords: Motion planning, Driving simulator, Acceleration perception, Optimization

Introduction

Experience and experimentation have always played an effective role as tools for human evolution in advancing science, education, and learning. In many cases, due to reasons such as human risks, the high cost of experimental tests, the need for experiencing unusual conditions to increase individuals' confidence or for educational purposes, it may not be feasible to conduct experimental tests. In such circumstances, the presence of virtual environments or simulations becomes essential, which, the closer they resemble reality, can have a greater impact by providing a realistic experience.

In the 19th century, when the lack of training and experience among pilots led to disasters, the idea of using simulators was first introduced and implemented at the Antoinette flight school in France [1]. Their simulator consisted of a half-barrel mounted on a universal joint, aiming to train pilots in maintaining balance against external forces. The successful experience of this simulator paved the way for the construction of simulators in other fields, including spacecraft, rail vehicles, ships, and driving.

These simulators utilized various mechanisms depending on the user's needs, but the introduction of the Stewart platform in the second half of the 20th century marked a new phase in the world of simulators [2]. Among the advantages that led to a high demand for this platform were its high load capacity, absence of locking points in the mechanism, suitable response to external loads, low maintenance costs, and the ability to achieve high precision.

In the field of driving simulators, the Volkswagen simulator, built in the early 1970s, can be mentioned as the first driving simulator [3]. This simulator consisted of a cabin and a display screen installed on the hood in front of
the windshield. Shortly after, using the experience from this German simulator, the Swedish Road Administration designed a complex and advanced simulator that had many features similar to current simulators [4].

The 1990s marked a period of increasing focus on acceleration and motion. The Stewart mechanism with six degrees of freedom was one of the prerequisites for achieving this goal at that time. Various companies successively produced simulators using this mechanism, each claiming to provide the best driving experience. In 1993, simulators entered a new phase of driving simulation by adding separate lateral movement, commonly referred to as advanced driving simulation. However, the evolution of driving simulators during those years occurred at the Leuven University simulator [5] and the Toyota simulator [6]. They mounted the Stewart mechanism on a platform with two degrees of freedom in the horizontal plane, thus creating an 8-degree-of-freedom platform. Another advantage of their work was that the car was fully enclosed within them, making the simulation appear more realistic.

In general, advanced simulators, including advanced driving simulators, are very costly. Firstly, they require ample space and high technology, and secondly, most of them are developed individually based on demand.

This research aims to create the sensation of presence in a desired movement during driving conditions without the presence of the actual movement or a complex mechanism with high degrees of freedom. Given the lower degrees of freedom of the mechanism in motion, movement planning in the variable state space model is optimally performed based on the most similar acceleration in two directions.

The sensation of movement in humans generally relates to three types of receptors [7]: proprioceptors, which report the overall position of the individual [8]; the vestibular system or auditory acceleration sensor, which primarily perceives acceleration and is located in the inner ear; and vision, which can induce an illusion as reality to an individual [9]. In this research, acceleration at the point of the vestibular sensor (vestibular sensor) is targeted as the most important acceleration sensor in the human body, and optimal state variables in the simulator will be obtained over time to simulate the desired acceleration profile corresponding to a virtual movement in this sensor.

3- Methods

a) Mechanical Model

A general movement involves translation and rotation. The vestibular sensor perceives only translational movement, which can be described with three longitudinal or horizontal components: front-back, lateral: left-right, and vertical: up-down.

In general driving, although all three translational movements are experienced (rotations will also be perceived as linear acceleration in the sensor and will be added to net linear acceleration), due to the inherent structure of vehicles, longitudinal motion is predominantly significant. Therefore, longitudinal acceleration is the most important component that creates the sensation of movement during driving. Vertical acceleration on a smooth and straight path will be equal to gravitational acceleration (g), and due to path irregularities and path curvature in the longitudinal-vertical plane, slightly higher or lower values than g will be experienced. Lateral acceleration is caused by path curvature in the longitudinal-lateral plane, as well as asymmetric road irregularities.

The current research, which aims to develop an algorithm for generating optimal motion curves in state space, limits the path to the longitudinal-vertical plane for simplicity and reconstructs horizontal acceleration curves based on the driver's desired movement, while vertical acceleration curves closely follow the value of g. The numerical solution method will be easily extendable to lateral acceleration curves.
Thus, the dynamic model consists of a cabin with two degrees of freedom of displacement and rotation (Figure 1). The x and y axes are longitudinal and vertical axes in real space, and the u and v axes are longitudinal and vertical axes in virtual space, i.e., from the passenger's perspective. The z-axis is perpendicular to all four axes. The cabin can move in the x direction and rotate (θ, counterclockwise: positive) around the z-axis.

Due to experimental conditions, the movement of the cabin in the x direction is restricted, so to create desired horizontal acceleration (from the passenger's perspective, along the u direction), assistance is taken from gravitational acceleration by applying a part of gravity along this direction through cabin rotation. A slight change in angle has a negligible effect on vertical acceleration from the passenger's perspective (along the v direction), but even a slight change, if significant over time, adds sentences to both axes. Therefore, the desired horizontal and vertical accelerations must be solved with a set of horizontal and rotational movements.

b) Kinematic Analysis

The acceleration of the auditory sensor point (A in the figure) from the observer's perspective on the ground, in the u-v cabin system, is expressed as follows:

\[
\begin{align*}
a_u &= (\ddot{r} - r(\ddot{\theta} + \dot{a})^2)\cos(\alpha) - (r(\ddot{\theta} + \dot{a}) + 2\dot{r}(\ddot{\theta} + \dot{a}))\sin(\alpha) + \ddot{\theta} \cos(\theta) + g \sin(\theta) \\
a_v &= (\ddot{r} - r(\ddot{\theta} + \dot{a})^2)\sin(\alpha) + (r(\ddot{\theta} + \dot{a}) + 2\dot{r}(\ddot{\theta} + \dot{a}))\cos(\alpha) - \ddot{\theta} \sin(\theta) + g \cos(\theta)
\end{align*}
\]

Where \( a_u \) and \( a_v \) are the accelerations of the auditory sensor in the horizontal and vertical directions from the passenger's perspective, respectively. Assuming that the individual is stationary relative to the cabin, the equations simplify to the following form:

\[
\begin{align*}
a_u &= -r \cos \alpha \ddot{\theta}^2 - r \sin \alpha \ddot{\theta} + \ddot{X} \cos \theta + g \sin \theta \\
a_v &= -r \sin \alpha \ddot{\theta}^2 + r \cos \alpha \ddot{\theta} - \ddot{X} \sin \theta + g \cos \theta
\end{align*}
\]

Unconstrained Motion; In cases where the range of variation of state variables is not limited, and the desired vertical acceleration is simply gravitational acceleration, the response to any desired horizontal acceleration function will only involve displacement along the horizontal axis without cabin rotation.

Slow-motion; When the values and changes in the desired horizontal acceleration are small relative to gravity, and the values and changes in the difference between the desired vertical acceleration and gravitational acceleration are also small relative to gravity, small changes in the state variables will result. Therefore, disregarding \( \ddot{\theta}^2 \) and \( \ddot{\theta} \), equations 3 and 4 are reduced to:

\[
\begin{align*}
a_u &= \ddot{X} \cos \theta + g \sin \theta \\
a_v &= -\ddot{X} \sin \theta + g \cos \theta
\end{align*}
\]

And the response in state space will be as follows:

\[
\begin{align*}
\ddot{X} &= \sqrt{a_u^2 + a_v^2} - g^2 \\
\theta &= \sin^{-1}\left(\frac{ga_u - a_v \ddot{X}}{a_u^2 + a_v^2}\right)
\end{align*}
\]
In this method, the solution for each moment is independent of other moments, which is considered an advantage. However, on the other hand, the range of equations (4) and (5) is limited and does not provide a solution for most input horizontal and vertical accelerations. However, when the real solution to the problem is not within the solution domain of the equation, the solution can be guessed using previous and subsequent moments that satisfy the domain. But after observing the graphs, it is crucial to note two very important points: the solution is guessed interactively based on guessed subsequent and previous solutions, which cannot simulate acceleration in real-time. Additionally, executing the profile under laboratory and limited workspace conditions is impractical; therefore, X and $\dot{\theta}$ must be optimized based on space constraints.

c) General Numerical Solution:

Equations (1) and (2) are solved for $\ddot{\theta}$ and $\dot{X}$:

\[ \ddot{\theta} = \frac{a_v \cos(\theta) + a_u \sin(\theta) + r(\dot{\theta})^2 \sin(\alpha + \theta) - g}{r \cos(\alpha + \theta)} \]  
\[ \dot{X} = a_u \cos \theta - a_v \sin \theta + r \dot{\theta}^2 \cos(\theta + \alpha) + r \ddot{\theta} \sin(\theta + \alpha) + g \sin 2\theta \]

With a given function or array for the desired horizontal and vertical accelerations ($a_v$ and $a_u$) over time, and starting from specific initial conditions (naturally chosen as zero: $\theta_0 = 0$ and $\dot{\theta}_0 = 0$), if the denominator of the equation for $\ddot{\theta}$ does not become zero (or close to zero), equations 5 and 6 are solved using one of the numerical solution methods (e.g., fourth-order Runge-Kutta), and X and $\theta$ are obtained over time. However, in solving equations for many desired acceleration functions ($a_v$ and $a_u$) measured in real-world driving scenarios, the denominator of the equation for $\ddot{\theta}$ tends to zero, and the equations do not have a solution. This is due to the inability to execute the specified desired acceleration functions ($a_v$ and $a_u$) using this two-degree-of-freedom model. A discussion on the existence of a solution will be conducted later in this text.

d) Optimal State Functions:

When the desired acceleration functions cannot be exactly executed, we execute the closest executable functions to them. This principle underlies the final response in this section.

The cost function is defined as the integral of squared errors in the horizontal and vertical acceleration spaces, and we solve the resulting nonlinear optimization problem. Since the design variable in this problem is a function (path), and the cost function is a scalar function of it, for numerical solution, we encode the path into a vector of intermediate points in state space. To transform the constrained optimization problem into an unconstrained one, penalty functions replace constraints on state variables. Multidimensional optimization algorithms (such as gradient descent methods with variable step size) can be used to solve this problem.

4- Results

For numerical solution and result analysis, profiles of horizontal and vertical accelerations have been provided to the program as arrays. As an example, the following general motion is considered and analyzed:

The motion starts from rest with an acceleration of 3 meters per square second over 8 seconds on a straight path, then comes to a sudden stop within 5 seconds, accelerates again to reach a speed of 2 meters per second, and finally passes over a street bumper with an altitude of 0.15 meters and a width of 1.5 meters at constant speed. The radius of the car’s wheels is assumed to be 0.325 meters.

Chart 1 illustrates the results obtained from solving analytically for a pair of desired accelerations for vertical and horizontal directions. The numerical solution is performed to find the state variables, and the resulting accelerations from the solved state variables are also shown. It is observed that both
accelerations tend towards infinity in the seventh second, and the solution cannot proceed beyond this point. The reason is the infeasibility of the given acceleration pair.

For the provided profile above, the solution is performed assuming small temporal changes, and the results are presented in chart 2. It can be observed that initially, the virtual acceleration is close to the real acceleration, but as time progresses, this error increases.

The same problem is solved numerically for two types of constraints on state variables, solely using the degree of freedom in translation, and is illustrated in chart 3. The importance of cabin rotation is evident. The path is solved again for translation and rotation variables, resulting in much better outcomes (chart 4). For comparison, the results of different solutions are presented collectively in chart 5.

Chart 1. The generated acceleration profile (Actual $a_{u}$) resulting from the analytical solution using the fourth-order Runge-Kutta and Fulberg methods. Both charts tend towards infinity in the seventh second, indicating that the given acceleration profiles are not accurately implementable by the discussed two-degree-of-freedom model.

Chart 2. The solution plot with the assumption of small-time variations. Virtual $X$: The space in which the driver drives in the virtual environment. Actual $X$: The space provided for the driver under laboratory conditions.

Chart 3. The solution plot using only translational motion without rotation, under two different constraints for the workspace: Actual 1 simulates a change in $X$ within a range of 1 meter, and Actual 2 simulates a change in $X$ within a range of 2 meters.
Chart 4. The solution plot with different workspace constraints using optimization method. In this solution, both translational and rotational motions of the cabin are considered. The Actual 1 curve simulates a change in $x$ within the range of -0.7155 to 0.76040 meters, and the Actual 2 curve simulates a change in $x$ within the range of -0.0621 to 2.9848 meters.

5- Discussion

Existence of Analytical Solution; In problem 1, the vertical acceleration equals $g$, and by simplifying the equations, the unique solution is $\theta = 0$ and $\ddot{x} = a_u$. This means the driver is driving completely freely in open space, and as mentioned, this solution is not executable in the limited laboratory space.

Regarding problem 2; while changing position, the angle also changes. The biggest error in this part is the tendency of the solution to infinity in the iterative solution of the Runge-Kutta method (Chart 1).

For this problem, the following probabilities have been examined:

a) Computational Error: The resulting error occurred due to computational inaccuracies resulting from the accumulation of errors in each iteration of the Runge-Kutta solution. In this section, most numerical solution methods were rigorously examined for accuracy, but still, all solutions tended towards infinity.

b) Equation Problem: In this part, by adding a fitting numerical solution, the system behavior was predicted when the denominator of Equation 2 approaches zero. However, this method cannot provide the overall behavior of the system, and it did not yield solutions for all input profiles.

c) Direct Search Method: When the denominator approaches zero, the best acceleration, which has the smallest distance from the requested acceleration, was chosen. As a result, the profile chart improved significantly, but in some cases, it tended towards infinity. By maximizing the calculation accuracy, the error in horizontal acceleration increased significantly.

Therefore, the analytical solution is an unreliable method for this problem.

Uniqueness of Solution: Kinematic analyses are often among the most challenging dynamic analyses. In this regard, obtaining a solution from the inverse kinematics of the problem and creating a solution in the joint space is difficult, especially if the input data is acceleration. This makes the solution space highly sensitive, and consequently, the relationship between the solution in the input and output spaces is not one-to-one.

In the initial methods where the problem was analytically solved using the fourth and fifth-order Runge-Kutta method with very high accuracy, after a few seconds, all the charts tended towards infinity or, if not, this happened through manipulation in the algorithm, and it was not practical for all input acceleration profiles. Here it can be understood that because our system has two degrees of freedom, the joint space is very limited.

Workspace Constraint: In this problem, the workspace is limited, and unconstrained solutions are unusable (see figure 2). This constraint is only assumed for displacement changes, as increasing the angle makes creating solutions much more difficult according to kinematic equations, and there is no need to impose constraints on the angle. Furthermore,
the state space of the problem is also limited, as in some cases, it is not possible to run \( x \) and \( \dot{x} \) simultaneously, or the desired motion cannot be executed.

In the optimization algorithm, the angle changes between 0.5 to 0.3 radians. Considering Figure 3, where the acceleration generation process is performed only with a linear operator, the best workspace constraint is around 1 meter (Figure 3-1). If simultaneous changes in \( x \) and \( \theta \) are considered, the best workspace constraint is around 1.2 meters (chart 4-2). Although expanding the space limits better simulates the acceleration, chart 3-1 and 4-1 simulate the acceleration sensation better for the user.

Comparison of the Efficiency of Employed Algorithms:

As mentioned, in the optimization algorithm, the cost is the integral difference between the desired user acceleration and the provided acceleration. If this criterion cannot produce the optimal acceleration profile, the selection of optimization becomes intuitive and is defined based on the sensation of acceleration change. It is evident from chart 6 that sometimes the acceleration derivative graph is not differentiable, which the user will feel as a change in state. However, since the acceleration graph significantly smoothens during the control of the simulator operators, this problem can be overlooked.

An important point to consider is the increase in speeds and angular accelerations. Considering the profile of severe gas and brake provided in the example, this is expected. It should be added that the optimization was done in 20 seconds, and when the time is longer (for example, 2 hours), the computation volume and optimization dimensions increase. To solve this problem, optimization can be repeated every 20 seconds with new initial conditions.

Not considering constraints in the state space can be problematic for executing simultaneous \( x \), \( \theta \) profiles over time, which will be resolved in the future by examining optimal control problems.

Special Cases:

a) Only Angle Change: It is inferred from Equation 1 that when \( x \) equals zero over time, the system changes to two equations and one unknown. In this part, the best angle path that creates the least error in equations was selected as the chosen answer (Figure 5-0). In this section, when the car accelerates, the angle increases, and when braking, the angle decreases. During movement from the bumper, the angle changes inversely with the vertical acceleration (\( a_v \)), which adversely affects the horizontal acceleration (\( a_u \)). This effect disappears with the addition of displacement changes (chart 5-x, 0).

b) Only Length Change: By observing Figure 5-x, this algorithm alone cannot continuously give the driver the sensation of gas or acceleration. In some parts, after pressing the gas pedal for a while, the driver no longer feels the acceleration and seems to be moving at a constant speed. With this method, the driver cannot have a good sense of their movement. However, this algorithm is still excellent for simple and flat paths, such as driving on a highway (or when the driver sees many cars moving with them, the ability to continuously accelerate is taken from them), and it does not have the cost of creating joint R and excessive torques.

c) Simultaneous Change in \( x \) and \( \theta \): As seen in chart 5-2, to simulate the sensation of acceleration, the sum of the effects of both \( x \) and \( \theta \) profiles on the simultaneous creation of accelerations \( a_u \) and \( a_v \) is created, and because \( x \) and \( \theta \) are coupled in creating accelerations \( u \) and \( v \), eliminating or not executing either has a significant effect on simulating the sensation of motion.

Effect of Model Constants on Perceived Acceleration:

Considering chart 7, when \( r = 0 \) and \( \alpha = 0 \) or when \( \alpha=90 \) or 270, the simulation of vertical
acceleration \((a_v)\) does not succeed at all in moving from the bumper. In other words, changing the angle \(\theta\) does not assist in changing the person's height with vertical acceleration and prefers not to change. When \(\alpha\) is equal to 0 or 180 or 15 degrees, but \(r\) is not equal to 0, the simulation of vertical acceleration \((a_v)\) does not support sudden changes in movement from the bumper but is very successful in creating a sensation of acceleration change. In general, smaller \(r\) values increase the need for \(x\) changes in some accelerations \(a_u\), and larger \(r\) values make the cost for changing \(\theta\) higher. For points within the body that perceive a slight sensation of acceleration, it is better for the center of rotation to be lower in the body. Ultimately, the best model parameters were obtained as \(r=2\) and \(\alpha=15\).

As outlined in the main body of the article, reaching a solution in the form of having the entire path ready is provided. Additionally, predicting behavior is very difficult, and the use of greedy optimization algorithms severely reduces the quality of the answer. For this purpose, several gas and brake profiles are used in different conditions, and the behavior of the function is simultaneously guessed and executed for the user under working conditions with a similar filter.

By carefully examining chart (7) and observing the simultaneous changes in the behavior of \(\theta\) and \(x\) with changes in acceleration \(a_u\) and \(a_v\), it can be understood that when the path is not steep or there is no bumper, the behavior of the angle is strongly similar to the behavior of \(a_u\). In this case, in smooth paths, the angle can be guessed based on \(a_u\) and then the behavior of \(x\) can be determined based on \(\theta\) and \(a_u\), and \(a_v\).

6- Conclusion

In this study, based on a mechanical model with only two degrees of freedom, the acceleration of the passenger's head was produced as the most important point in understanding acceleration, with the best adaptation to a real motion so that the passenger feels like they are moving just like in a specific driving situation.

The simplicity of the mechanical model used makes this study a practical basis for designing cost-effective driving simulators. However, a major processing constraint is the simultaneous
scheduling of the entire motion profile, such that motion model scheduling is performed within a time interval with the entire motion profile available. As a major step in the development of this research, optimizing the motion of the mechanical model at any given moment based on previous and current data is proposed. Furthermore, by adding a vertical degree of freedom to the mechanical model while maintaining the simplicity of the set, it is hoped that the quality of simulation and the sensation of realistic driving in movements with significant changes in the vertical acceleration component, such as passing over bumps and bridges, will be further improved.

7- References


