1.0 Introductions

Driving simulators are often used in educational and research purposes. Driving Simulators’ capability in producing a virtual driving environment resembling real driving condition can be used to train novice drivers before they are exposed to the real world. Aside from that, driving simulators are important in data collection for road safety research, human factor study, vehicle system development and also traffic control device development. These allow designers, engineers as well as ergonomists, to bypass the design and development process of detailed mockups of the automobile interiors for human factor and vehicle performance studies.

Driving simulators range in complexity, capability and can be classified into 3 major groups: high, medium and low-level driving simulator. Figure 1 shows the classification of driving simulators. Some examples of high level simulators are, the National Advanced Driving Simulator NADS in IOWA, USA and the Toyota Driving Simulator in Susono City, Japan which started its operation on Nov 2007. These high level simulators have sophisticated systems such as a dome with 360 degree projection screen for virtual environment generation. They are also equipped with a full vehicle cab and a large motion platform which can mimic the driving conditions. Low level simulators can be relatively simple which only require personal computer or graphical work station, monitor and a simple cab and driving controls. Between these two extremes is the mid-level driving simulator. Mid-level driving simulators can have adequate
fidelity, validity and realism; yet affordable compared to the “world class” or high-level driving simulator. With proper configuration and harmonization of the visual, motion and cues, they can perform a wide range of driving scenarios and tasks. Figure 2 shows a few example of driving simulators.

**Figure 1:** Driving simulator classification.

- a. Toyota driving simulator
- b. 5DT driving simulator
- c. National Advance Driving Simulator
- d. Honda driving simulator
2.0 Project Objective

Road safety has always been a major concern for the Malaysian Government. The rapid increases in motor vehicle ownership in combination with the relatively young age of the populations and wide mix of vehicle types in the recent years have resulted in a significant increase of road safety problems. Various engineering approaches have been taken by the Government to overcome the problem. They are proactive actions, reactive actions, road maintenance and building new roads. In conjunction with the effort in the proactive actions, a research in developing a driving simulator was started in 2002 in Universiti Teknologi Malaysia by the Engineering Visualisation Research Group (EngViz). The driving simulator will provide the platform for future research related to road safety and transport. At the end of the first stage of the research, a fixed base driving simulator with Visual Database and a generic vehicle dynamic model, also known as Universiti Teknologi Malaysia Vehicle Dynamic Model (UTMVDM) was developed. A topographical-based visual database based on Universiti Teknologi Malaysia landscape was successfully constructed using virtual reality technology. A simple driver’s cabin with generic vehicle dynamic model (UTMVDM) is also developed. The developed vehicle dynamic model is compatible for operator-in-loop simulation requirements of a low cost fixed-base driving simulator.
The second stage research work was aimed to integrate a motion platform to the existing fixed based driving simulator. While driving a vehicle, a driver experiences the ride and handling characteristic of the vehicle through motion cues due to angular and linear accelerations of the vehicle chassis. The motion platform for driving simulator is a mechatronic equipment that is capable of giving the realistic feeling of a actual vehicle to the drivers. This is a research that involves multidisciplinary engineering skills. It is divided into 3 parts which is the motion platform mechanism design and fabrication, control system design and simulation and finally the integration of both control and actual model. Figure 4 shows the overall project layout.
3.0 Motion Platform Mechanism Design and Fabrication

The motion platform design is based on the Stewart platform design configuration. Stewart platform is selected because it is parallel robot manipulator with 6 parallel links which is capable of moving in 6-DOF. The upper platform connects all 6 parallel links forming a closed loop mechanism. This allows the platform to have good performance in terms of accuracy, rigidity and capable of handling large payload. The motion platform design is shown in figure 5.
4.0 Motion Platform Control System Design and Simulation

4.1 Motion Platform System layout

The motion platform is interfaced with control model in order to perform the 6-DOF motion cues. The motion platform system layout is presented in figure 6. First, the desired motion platform positions are fed into the simulation model from the UTMVDM. The motion platform simulation model then calculates the required actuators length to perform the motion cues. The model sends the input signal and passes through a PID controller to the data acquisition system (DAQ). In the mean time, the simulation model also passes the output data to SimMechanics. Communication between the mathematical model and DAQ is established using S-Function written in C programming language. The digital signal is converted to analog signal and pulse width modulation (PWM) signal to control the motor driver which drives the DC actuator. The DC actuator position signal is retrieved using potentiometer. The signal is converted to digital signal through the DAQ and filtered with low pass filter before feedback to Proportional-Integral-Derivative Controller (PID) as error signal. This completes the close-loop control system.
In this project, Proportional-Integral-Derivative controller is used and tuned using Ziegler-Nichols and approximation method. PID controller is by far the most common control algorithm among the control strategies. It is a control strategy that has been successfully applied in various processes over many years. The reason behind this is due to its simplicity, robustness and ability to suit in wide range of applications. For ZN PID controller tuning, the gain value is first increased until the closed-loop system becomes critically stable. The $K_u$, which is the gain value is recorded together with the corresponding oscillation period, $T_u$ of the system. $T_u$ is also known as the ultimate period. Based on the ultimate properties, the tuning parameters is calculated. Table 1 shows ZN PID tuning parameters. In this project, ZN method was able to give an overall guideline in tuning the motion platform control. The PID value is then retuned through approximation or heuristic tuning method.
### Table 1: Ziegler – Nichols PID tuning parameters

<table>
<thead>
<tr>
<th>Ziegler–Nichols</th>
<th>$K_u$</th>
<th>$\tau_I$</th>
<th>$\tau_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>$K_u/2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PI</td>
<td>$K_u/2.2$</td>
<td>$P_u/1.2$</td>
<td></td>
</tr>
<tr>
<td>PID</td>
<td>$K_u/1.7$</td>
<td>$P_u/2$</td>
<td>$P_u/8$</td>
</tr>
</tbody>
</table>

### 4.2 Motion Platform Kinematics

The kinematics of a robot manipulator describes the relationship between the motion of the joints of the manipulator and the resulting motion of the rigid bodies which form the robot. Kinematics can be divided into forward and inverse kinematics. The main role of forward kinematic of a parallel robot is to determine the position and orientation of the mobile platform is the actuators or parallel chain’s lengths are known. This problem has no known closed form solution. The forward kinematic of a Stewart platform can be mathematically formulated in several ways with each having pros and cons. Computation becomes a complex situation when optimization and adaptation is required to obtain an efficient procedure in forward kinematics solution. On the other hand, inverse kinematic provides one exact solution to solve the problem of determining the actuators length for a given position and orientation of the upper platform. Inverse kinematics is applied in this project because it provides a starting line for determination of the requirements and limitations of the driving simulator motion platform.
Figure 7 shows the vector diagram for a typical Stewart platform. Frame \{P\} is located at the center of upper platform and frame \{B\} is at the center of lower platform.

Figure 7 also shows that the \(Z_P\)-axis is pointing upwards and \(X_P\)-axis is perpendicular to the line connecting \(P_1\) and \(P_6\). The angle between \(P_1\) and \(P_2\) is denoted by \(\theta_P\), and the angles between \(P_1\) and \(P_3\), \(P_3\) and \(P_5\) is 120°. Similarly for base platform, \(X_B\)-axis is perpendicular to the line connecting \(B_1\) and \(B_6\), the angle between \(B_1\) and \(B_2\) is denoted by \(\theta_B\) and angles between \(B_1\) and \(B_3\), \(B_3\) and \(B_5\) is 120°. Later, the angles between \(PP_i\) and \(X_P\) is denoted by \(\lambda_i\) and angles between \(BB_i\) and \(X_B\) by \(\Lambda_i\). Next, \(\Lambda_i = 60^\circ - \theta_B/2\); \(\lambda_i = 60^\circ - \theta_P/2\) for actuators 1, 3, 5 and \(\Lambda_i = \Lambda_{i-1} + \theta_B\); \(\lambda_i = \lambda_{i-1} + \theta_P\), for actuators 2, 4, 6. Leg vector \(^Bq_i = (q_{ix} \ q_{iy} \ q_{iz})^T\), with respect to the frame \{B\}, can be express by the following equations.

\[
^B q_i = ^B d - ^B b_i + ^PR^p p_i
\]

\[
^B d = [x \ y \ z]^T \text{ is the position of frame \{P\}}
\]
The Vector $^pP_i = (p_{ix} \ p_{iy} \ p_{iz})^T$ describes the position of the attachment point $P_i$ with respect to frame {P}, and vector $^bP_i = (b_{ix} \ b_{iy} \ b_{iz})^T$ as the position of the attachment point $P_i$ with respect to frame {B}, then they can be written as $^pP_i = [r_p \cos \lambda_i \ r_p \sin \lambda_i \ 0]^T$ and $^bP_i = [r_b \cos \Lambda_i \ r_b \sin \Lambda_i \ 0]^T$ for $i = 1, 2, \ldots, 6$ where $r_p$ and $r_b$ represents the radius of the upper platform and base platform, respectively.

The $^pR_p$ represents the orientation matrix whereby

$$R_y = \begin{bmatrix} \cos \gamma & -\sin \gamma & 0 \\ \sin \gamma & \cos \gamma & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R_p = \begin{bmatrix} \cos \beta & 0 & \sin \beta \\ 0 & 1 & 0 \\ -\sin \beta & 0 & \cos \beta \end{bmatrix}$$

$$R_r = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha & -\sin \alpha \\ 0 & \sin \alpha & \cos \alpha \end{bmatrix}$$

And by combining 3 matrixes, we obtain

$$^pR_i = R_y R_p R_r \begin{bmatrix} \cos \gamma \cos \beta & \cos \gamma \sin \beta \sin \alpha - \sin \gamma \cos \alpha & \cos \gamma \sin \beta \cos \alpha + \sin \gamma \sin \alpha \\ \sin \gamma \cos \beta & \sin \gamma \sin \beta \sin \alpha + \cos \gamma \cos \alpha & \sin \gamma \sin \beta \cos \alpha - \cos \gamma \sin \alpha \\ -\sin \beta & \cos \beta \sin \alpha & \cos \beta \cos \alpha \end{bmatrix}$$

(2)

With $\alpha$ (Roll/ X angle), $\beta$ (Pitch/ Y Angle), $\gamma$ (Yaw/ Z angle).

Thus the length $l_i$ (Leg) of vector $^bP_i$, can be computed into equation (3).
\[ l_i = x^2 + y^2 + z^2 + r_p^2 + r_B^2 \]
\[ + 2(r_{11} p_{\alpha} + r_{12} p_{\beta})(x - b_{\alpha}) \]
\[ + 2(r_{21} p_{\alpha} + r_{22} p_{\beta})(y - b_{\beta}) \]
\[ + 2(r_{31} p_{\alpha} + r_{32} p_{\gamma})z - 2(x b_{\alpha} + y b_{\beta}) \]  

Equation 3 is then used extensively in developing the motion platform mathematical model for controlling the actuators length in performing 6-DOF motion task. The developed motion platform mathematical model (Inverse Kinematic Model) is shown in figure 8 and figure 9.

![Figure 8: Inverse Kinematic Model](image-url)
4.3 SimMechanics Motion Platform Generation Process

In order to investigate the performance of the developed inverse kinematic model, SimMechanics is introduced in this project. Based on 6-UPU motion platform configuration, a simplified motion platform is developed for SimMechanics. The simplified motion platform is aimed to reduce the total mechanical component yet retaining the main characteristic of the motion platform such as types of joint and its corresponding location. After modeling a simplified motion platform, CAD translation tool is used to transform geometric CAD assemblies into Simulink block diagram model. The CAD translation tool first exports the assembly model from CAD platform into physical modeling file with xml extension. The physical modeling file is then imported into Simulink, creating a SimMechanics model. Figure 10 shows the sequence of CAD to SimMechanics transformation.
The imported xml file will be converted to a SimMechanics block model. The generated SimMechanics model can be visualized while the simulation is running. Figure 11 shows the simplified motion platform in CAD platform and model after it is converted into SimMechanics.

The SimMechanics motion platform (SimPlatform) is incorporated with inverse kinematics model for actuation control (Figure 12). The inverse kinematic model controls the actuators to extend and/or retract relatively to one another. The complete SimPlatform Model allows the motion platform motion cues to be visualized. This also helps to test and validate the performance of inverse kinematics model.
Figure 12: Complete SimPlatform with inverse kinematic block

4.4 Motion Platform Graphic User Interface (UTMMP GUI)

Figure 13 shows the motion platform graphic use interface (UTMMP GUI) is developed for the whole UTM motion platform system control. UTMMP GUI provides controls for the motion platform actuators. It is divided into 5 parts which are colored orange, blue, red, yellow and green. The orange colored subsystem is the Simulink Execution Block. It controls the execution of a Simulink model and allows simulation to run in real time or a factor of real time. The blue subsystem indicates the input source which is the inverse kinematic model developed in the earlier stage. It calculates the desired actuator position for a given the vehicle dynamic input and sends the signal as input for UTMMP GUI. The yellow subsystem is where S-function calls for data acquisition system. Green block is the PID controller. The controller can be tune by altering the parameters in the controller block. Finally is the red subsystem which acts as emergency stop. This is a crucial subsystem whenever the system is out of control, the manual switch can be trigger to stop the simulation immediately.
5.0 Motion Platform Hardware and Simulation Integration

After the motion platform is constructed, the motion platform is installed and connected to the simulation model through data acquisition system. The complete motion platform system (UTMMP) with data acquisition is shown in figure 14. Figure 15 shows the motion cues performed by the motion platform.
Figure 14: Motion Platform Complete Setup

a. Complete motion platform system

b. Motion platform

c. Electronic circuit
### Figure 15: Experimental result for motion platform movement

6.0 Conclusion

At the end of the research work, a 6-DOF motion platform prototype for vehicle driving simulator was developed. The motion platform is to provide the vehicle motion while traveling on different road surface conditions. The motion platform can not only be used as driving simulator but also other vehicle simulator such as small ships and aircraft. 6-DOF motion platform is also often used as earthquake shaking table, vibration platform and in seismic research. An earthquake shaking table or vibration platform is a device for shaking structural models and components with a wide range of simulated ground motions, including reproductions of recorded earthquakes. The motion platform can also
be used as positioning devices. With the capabilities of presenting good performance in terms of accuracy and rigidity, it can be applied in machine tool industries. Last but not least, the knowledge gain from the motion platform research process can be used as stepping stone for future automation, robotics, automotive related research and human factor studies.

The future works of the driving simulator project outline are as follows:

1. Motion platform washout algorithm design
   - Integrating of vehicle dynamic model and 6 degree of freedom motion platform
   - Reestablish the data communication between existing vehicle dynamic model and virtual database
   - Optimizing data transfer and simulation performance

2. Motion platform control and system refinement
   - Developed a complete Graphic User Interface for motion platform
   - Implementation of a sliding mode controller using high performance sensors
   - Perform circuitry building, power supply distribution and electronics packaging which is reliable and safe under standard regulations

3. Driving cabin design and instrumentations
   - Design and develop a driving simulator cabin
   - Possible of providing vehicle system development
   - Human factor studies and vehicle cabin ergonomics
   - Control and sensor setup