Development of the Several Integrated Degree-of-Freedom Demonstrator (SIDFreD) Simulator

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The topic of the paper is the design and development of the *Several Integrated Degree-of-Freedom Demonstrator* (SIDFreD) that was designed and built by the Carleton University Simulator Project (CUSP) team over the past two years. The design of SIDFreD allowed all of the students in the project to crystalize both theoretical and practical understanding of how components interact in a tightly integrated simulator. The design of SIDFreD also allowed the students and faculty to appreciate design in an inter-disciplinary environment. The inter-disciplinary design approach significantly benefitted the technical design of SIDFreD from the project specification through to the detailed design stages. The paper will present SIDFreD as a case study in inter-disciplinary design. The technical aspects of the SIDFreD design will be presented in detail. The integration of the inter-disciplinary nature of SIDFreD and correspondingly its design team will also be highlighted.

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1 Introduction

CUSP is an innovative, multi-year, multi-disciplinary project that is comprised of fourth-year students, graduate students, and faculty at Carleton University. One of its unique features is the inter-disciplinary aspect of the project, incorporating the knowledge and expertise from Mechanical, Aerospace, and Systems and Computer Engineering disciplines, as well as Business, Computer Science, and Psychology.

The long-term goal for CUSP is to develop a multi-functional vehicle simulation facility at Carleton University with a six-degree-of-freedom motion platform capable of accepting interchangeable cockpits, controls, and software to simulate any vehicle desired using the six-degree-of-freedom motion platform and a general visual and acoustic cues system. The facility will be used to support mathematical modelling and simulation teaching as well as research activities.

Modern simulator motion platform design must be undertaken based on complete consideration of the human factors aspects of how users sense motion; the computational architecture must be open such that the resulting simulator can be interfaced with evolving computational technology, maintained, and connected with other remote simulators; the facility must include high-fidelity vehicle models; and the project must be undertaken with an associated sustainable business plan. The level of success of SIDFreD is the direct result of deliberate inter-disciplinary design.

The topic of the paper is the design and development of the *Several Integrated Degree-of-Freedom Demonstrator* (SIDFreD), a research platform on which new technology and methodologies can be tested and implemented. SIDFreD will also provide a teaching and learning aid for future project members, in addition to a multi-functional simulation facility. The demonstrator includes a three-degree-of-freedom motion platform capable of accepting interchangeable cockpits, High Level Architecture (HLA) compliant software for simulating a variety of vehicle types, and a versatile visual system.

Currently, SIDFreD simulates an on-road vehicle using a lateral translational platform (1^{st} degree of freedom) to simulate the lateral acceleration of the road vehicle, and a rotational platform (2^{nd} and 3^{rd} degrees of freedom) to represent the roll and pitch of the vehicle during cornering, acceleration, and braking. As a learning tool, the students were able to implement and test the concepts that are being considered for a subsequent six-degree-of-freedom simulation facility.

2 Design

The SIDFreD motion platform was designed in two stages: the translational motion and evaluation cockpit, completed in Year 1 of the project; and the expansion to include platform rotation, completed in Year 2 of the project. The design associated with translation and rotation will be presented sequentially.

2.1 Translational Motion

The 1^{st} degree of freedom is the sway translation of the base platform used to simulate the longitudinal or lateral accelerations. The platform's range of motion is roughly proportional to the duration for which accelerations can be sustained. The general configuration is illustrated in Figure 1.

The sway platform runs on a centralized guide rail with two pillow block bearings and four fixed wheels at the corners that run on I-beams. The two precision-aligned I-beams lie on the facility's carefully-levelled floor. This is critical to ensure consistent operation and performance of the platform.

During the design and manufacturing of the lower platform, special consideration was given to maintaining structural stiffness since stiffness is important to ensure consistent fidelity during simulation. As a result, the platform was manufactured from welded 2 in by 1 in structural steel box beam. The steel cockpit floor and aluminum superstructure was bolted to this platform.

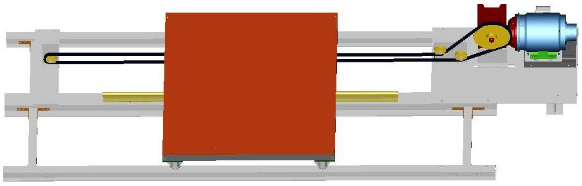

Figure 1: SIDFreD translational platform ProE model

The aggressive nature of the required platform motions and the platform weight were most demanding. The most general motor abilities desired were reversibility and variable operation settings. The motor had to be reversible so that the platform could be quickly accelerated in either direction. It had to be able to operate at various speeds and torques since the platform will always be moving at different speeds.

The motor specifications that were set out by the SIDFreD team included: a maximum payload of 500 lbs, a peak acceleration of 0.5 g, and a maximum platform displacement of ±1.5 ft from centre position.

A 2 hp vector motor and controller were chosen as the actuation system. The cockpit platform is driven by a gear-reduced chain drive motor configuration, controlled via a serial interface. The chain attaches to the platform at the centre of mass, thus avoiding the application of any torque on the centralized guide rail. The translational base has been designed such that it includes an integrated chain guard covering the entire run of the chain. Therefore, a raised platform is required to be attached to the translational platform to allow the chain guard to pass under it and allow the 2^{nd} and 3^{rd} degrees of freedom to be mounted above it.

2.2 Rotational Motion

The 2^{nd} and 3^{rd} degrees of freedom consist of an angular displacement platform capable of roll and pitch motions superimposed on the translational platform. Two vertical linear ball-screw actuators that are installed at right angles to the centre post are used to implement the 2^{nd} and 3^{rd} degrees of freedom, as illustrated in Figure 3.

Supported by the actuators and centre post is the upper platform, made from 6061-T6 aluminum, which is a structural grade with a high strength temper to ensure maximum stiffness. All aluminum members forming the upper platform will be welded together, while non-aluminum members, such as the steel centre post will be joined to the aluminum by rigid flanges and fasteners. The aluminum frame is fastened to the steel centre post via a flange welded to a zero-backlash universal joint. This joint is then welded to a 2 ft high, 3 in diameter low-carbon steel tube (see Figure 2). Minimizing twist in this design was critical because twist would be perceived by the user as inaccuracy of the simulation, and thus degrade the overall fidelity. Also by having a stiffer centre post, the structure will be able to transmit the motion more efficiently.

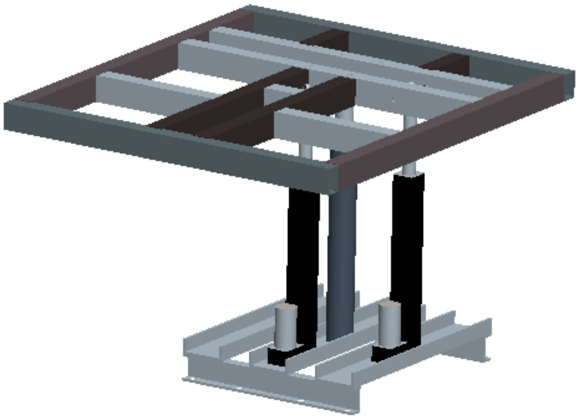

Figure 2: SIDFreD upper platform ProE model

The weight of this structure is extremely important, as the translational platform, along with the vector drive motor (see Figure 1) can actuate a maximum payload of 500 lbs and still meet the required motion specification. In order to optimize the weight of the platform, optimization studies using FEA techniques were performed. This maximized the efficiency of material use and reduced the overall weight of the second platform.

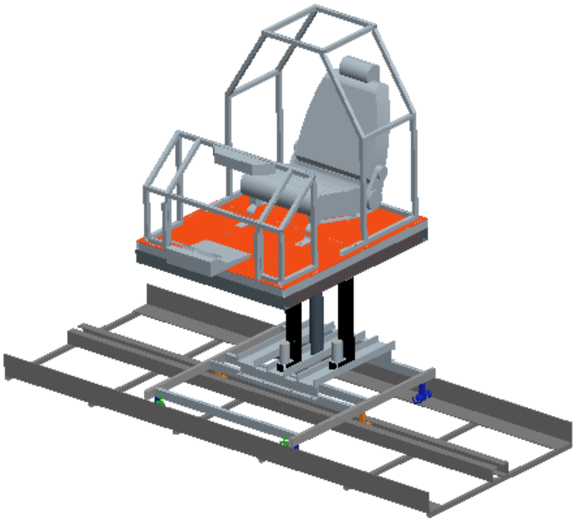

Figure 3: SIDFreD three-degree-of-freedom assembly

The actuators were sized to conform to SIDFreD design specifications of low cost, and low platform height, while meeting the required rotational velocity, force, and stroke length. Cost and platform height can both be reduced if the actuators are positioned closer to the centre post. The height is reduced by minimizing the stroke of the actuators, which is accomplished by minimizing the distance between the actuators and centre of rotation. The cost is largely influenced by the speed of the actuators, and the speed required is proportional to the fidelity desired and the distance from the actuators to the axis of rotation. Therefore, from this point of view, it is desirable to place the actuators as close to the centre post as possible. However, stability of the platform is also of importance, making the ideal actuator configuration a compromise between these platform design specifications.

Currently, SIDFreD is designed to simulate a 0.5 g lateral acceleration, but the acceleration curve that the occupant must feel is not well understood since requirements are deeply rooted in psychology and human factors. Using MATLAB simulations, it has been determined that to achieve a smooth 0 to 0.5 g transition in under 0.5 s, more than 60 deg/s of angular rotational velocity is required. While budget constraints do not allow the purchase of an actuator of this performance, dynamic analysis has shown that an actuator placed 9 in from the centre post with a stroke of 9 in, velocity of 4.5 in/s, force of 850 lbs, and acceleration of 16 $\mathrm{in/s^2}$ will provide an angular velocity of 30 deg/s, which will be sufficient. The platform motion created from a ”smoothed” unit step input of 0.5 g can be seen in Figure 4. In this instance, acceleration felt by the occupant has a time lag between the end of the onset provided by the translational acceleration and the sustained acceleration felt due to gravity through the rotation. This time lag is in the order of 0.5 s, and can be shortened by decreasing the onset acceleration value. Thus from a fidelity point of view, a higher angular velocity would have been desirable but was not financially possible.

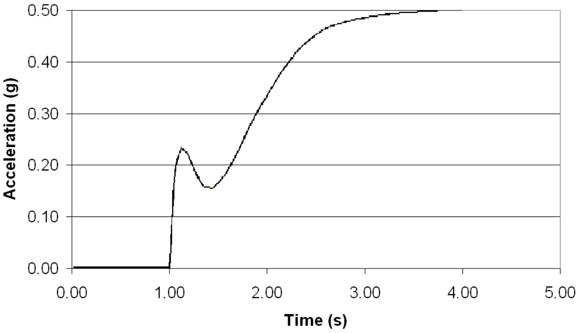

Figure 4: Washout motion

3 Safety

Safety was a major factor during facility design. In addition to compliance with university safety regulations, aspects specific to human-in-loop simulation were developed for this project. In terms of hardware, sensors, mechanical bumpers, computer system safety switches and a passenger restraint system were also developed and installed.

3.1 Bumper

In order to allow an occupant to operate the SIDFreD platform while it is in motion, certain safety requirements must be met. Bumpers at either end of the SIDFreD translational track will ensure that the demonstrator and the operator inside will come to a safe stop should the platform move too far along the track.

Aluminum foam was chosen as the bumper material. Aluminum foam is very porous, lending itself to the fabrication of components that are designed to collapse. As it is plastically deformed during impact, aluminum foam absorbs energy rather than elastically storing it. This energy absorption will reduce any rebound that SIDFreD and its operator may experience during emergency stopping should a runaway condition develop and other nonperishable safety systems fail.

The volume of aluminum foam required to make an adequate bumper can be obtained from the area under the stress-strain curve of the material, as shown in Figure 5. The area under the graph gives energy absorbing capability per unit volume.

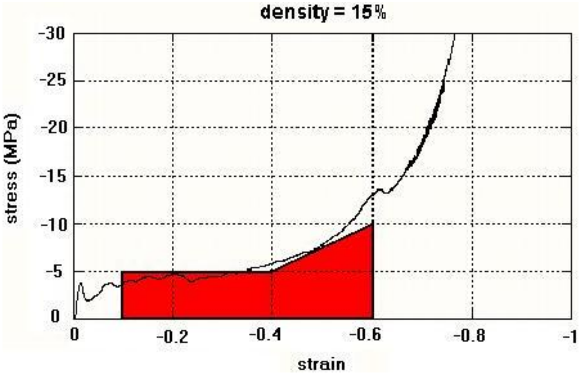

Figure 5: Bumper energy absorbtion

Since the primary task of the bumper is to keep the operator safe, the time interval over which SIDFreD comes to a stop is also important. By changing the bumper's surface area that comes in contact with the demonstrator platform in the event of a collision, the thickness of aluminum foam required to absorb any given amount of energy also changes. Since the platform will stop over the period of time it takes to absorb the platform's kinetic energy, deceleration can be adjusted accordingly.

3.2 Cut-off Switches

In addition to the main power disconnect, two emergency stop switches were installed in close proximity of where personnel would be stationed during simulator operation. One of the switches was integrated with the steering wheel assembly, while the other was installed by the keyboard of the PC workstation. These provide platform motion override access to both the simulator user and the operator. A third emergency shutoff cuts power to the motor controller in addition to the motor.

3.3 Cockpit and Harness

The cockpit superstructure configuration, in addition to serving as a location for mounting controls and a visual projector, protects the occupant during platform motion. Special consideration was also taken during the cockpit design to allow for convenient loading and unloading of the operator. The occupant is secured during simulation using a 5-point racing harness integrated into the seat.

4 Testing

The SIDFreD Data Acquisition System (DAS) consists of an optical mouse mounted to the base of the SIDFreD translational platform to monitor the platform's position and a program to read this information from the mouse, and store it for later analysis. For the implementation of the DAS software, a suitable method of acquiring position information was required. The two methods considered were Windows application programming interfaces and DirectX.

Microsoft Windows provides simple event-based application programming interfaces for using the mouse. This means that when the mouse is displaced, a message is sent to the program and the program can perform any actions associated with mouse movement. The problem with this is that it is focus-based, and if the mouse travels outside the window then the program will not be notified of further mouse events. Also, the Windows mouse system is cursor-based, and if the cursor travels to the edge of the screen, any movement past the edge will not be recorded. Finally, messages sent to a program enter a message queue, and if numerous messages are in the queue, there might be significant delay in the program receiving the message.

DirectInput provides a real-time solution for mouse access that alleviates the problems with the Windows APIs (Application Program Interface). DirectInput bypasses the Windows mouse controls and works directly with the hardware to provide real-time mouse access. Since DirectInput works directly with the hardware, there is no concern with the cursor and it is not limited by screen sizes. DirectInput is not as simple to use as the Windows APIs, but due to its speed and flexibility, DirectInput was used in the implementation of the DAS.

The optical mouse DAS outputs values to the computer in Mickeys (mky), the smallest unit of mouse displacement measurement, thus requiring calibration to SI units. This was accomplished by displacing the platform a measured distance and generating a conversion factor having units of mky/m, as shown in Table 1. The conversion factor was then coded into the DAS software to provide output displacement in SI units. As shown in Table 2, validation tests indicate an accuracy of 1.5 percent.

The DAS was used to produce data that would allow the testing team to determine the maximum acceleration of the translational platform with 0 lbs and

Table 1: Mouse calibration

Test	Motor RPM	Actual Disp.	Virtual Disp.	Conv. Factor
1	50	98.25	15819	161.01
2	100	77.00	12770	165.84
3	500	63.00	10335	164.05
4	150	79.25	13132	165.70
5	1000	69.75	11489	164.72
			Average	164.82

Table 2: Conversion factor verification

Check	Motor RPM	Actual Disp.	Virtual Disp.	Percent Error
1	100	48.25	48.54	0.60
2	500	66.50	67.50	1.50
3	50	70.25	70.84	0.84

300 lbs additional load to represent the 2^{nd} and 3^{rd} degrees of freedom. The platform was translated at 1.5 m/s in both configurations and acceleration data was collected. Results indicate negligible effects on acceleration performance.

A platform acceleration of 0.5 g under a 500 lbs load was predicted in the initial design calculations. These conditions were duplicated as a means of validating the platform acceleration data. Results indicate an average acceleration of $11.7\ \mathrm{m/s}^2$ or 1.2 g is achievable (see Figure 6). This discrepancy is due to conservative motor selection and will serve as a benefit to later design refitments. That is, as the platform increases in degrees of freedom and weight, the lateral performance is not expected to degrade below the required motion specification.

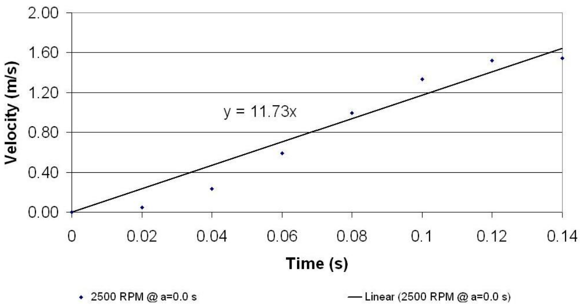

Figure 6: SIDFreD prediction

The SIDFreD platform will be required to change directions frequently. It was desired to determine the platform motion characteristics during such changes in direction. The platform was translated at +0.5 m/s and then a request to switch directions and travel at -0.5 m/s was given. Data indicates a maximum overshoot of 20 percent and a settling time of 0.25 s (see Figure 7). The scatter associated with the data occurs at a frequency of 5 Hz and it has been concluded that it is a result of processing lag while writing to the hard drive.

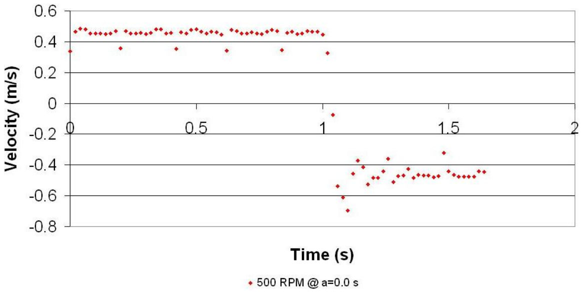

Figure 7: Translation reversal

5 Simulation Concepts

The interdisciplinary aspect of the project is integral to success. There are a variety of different simulation concepts that have roots in computer systems, psychology and engineering design. The platform's ability to provide accurate motion cues rely on the integration of all the concepts including user inputs, visuals and audio. Considering the extensive number of components and facility complexity it was necessary to secure funding from industry and research contacts. Budget constraints have had an influence on platform performance, however, industry-relevant learning experience has been the main goal.

5.1 Controls and Visuals

Currently, the simulation is controlled by the operator through an off-the-self USB Force-Feedback steering wheel, as well as accelerator and brake pedals. The simulation visuals are provided by a data projector mounted to the platform's superstructure and separate projection screen. This allows platform motion while maintaining visual reference, as seen in Figure 8. Increased funding in the future would allow upgrades to the visual system in the form of a head mounted display and head tracker. Research in this field indicates a minimum 60 Hz refresh rate is required to avoid sickness associated with visual stimulus.

5.2 HLA

The High Level Architecture (HLA) is a standard for simulation interoperability. The HLA takes a

Figure 8: SIDFreD cockpit and translational platform

component-oriented approach to simulation, and focuses on the ways in which the components of a simulation cooperate, i.e. interoperate, to achieve the objective of the simulation. One of the goals of the HLA is to encourage the reuse of components. Reusing components can reduce development time and increase the quality of the resulting software system. These gains are possible since the components already exist and have been tested previously. The HLA was proposed by the U.S. Department of Defense in the mid-1990's to address ambitious DoD modelling and simulation activities. An early draft of the HLA specification was given to the IEEE, and was subsequently revised and published as IEEE Standard 1516-2000.

In the HLA, individual simulation components are called federates, and the collection of components that realize a simulation is called a federation. The HLA specification consists of three parts: a set of ten rules that constrain federates and federations, a set of documentation standards for federates and federations, and the Runtime Infrastructure (RTI) programmer's interface (API). The rules governing federates and federations are very simple and easily applied. For example, one of the rules states that federates must only interact using RTI services. The documentation standards ensure that any information exchanged among federates is specified. This interfacing information is essential to achieve interoperation among federates. The documentation can be used for a variety of purposes prior to runtime; however, the information is also used at runtime in support of RTI services. The RTI is a middleware (software) layer that implements HLA services. The HLA only specifies the API, and therefore various implementations are possible.

The HLA was chosen as the underlying computing framework for CUSP platforms for several reasons. The use of a standard assists in development by providing a common terminology, scope and constraints for HLA-compliant designs. The HLA represents the state-of-the-art in terms of simulation interoperability standards. The HLA emphasizes interfacing issues in a component-oriented architecture, which encourages design considerations at an abstract level above the implementation code. The RTI middleware hides all RTI implementation details and enables federations to be distributed transparently across a network, which in turn allows the incremental scaling of the processors supporting the federation without requiring additional programming. Developing HLA-compliant simulators enables the potential to integrate CUSP platforms as components in larger simulations. In addition, one of the Lead Engineers had experience with the HLA and was confident that the HLA would be a valuable asset to the project.

To date, the HLA has been very successful in its support of SIDFreD. Student teams have developed HLA-compliant SIDFreD simulators, which have performed real-time simulation involving hardware and humans in the loop. The component-oriented nature of the HLA has been instrumental in allowing the system architecture to evolve to include additional components (federates) to address safety, washout, testing infrastructure, and new vehicle models. The only drawbacks to the HLA have been the steep learning curve associated with the breadth of the RTI, and the lack of readily available examples that are relevant to CUSP. The RTI services have been designed to support a broad range of simulation styles, and effort was required to build a demonstration system to address the issues relevant to the project. Once SIDFreD development was organized around the HLA demonstration example, development proceeded significantly more smoothly. As future versions of SIDFreD introduce additional complexity, early experience suggests that the HLA will scale up to meet the increasing demands.

5.3 Washout and Human Factors

Human factors and *Washout* represent a key point of intersection between the fields of human physiology, psychology, cognitive science, and engineering. The implementation of a convincing motion simulator starts by modelling how the proprioceptive, visual, and vestibular receptors respond to force and motion cues encountered during actual operation of the vehicle be-

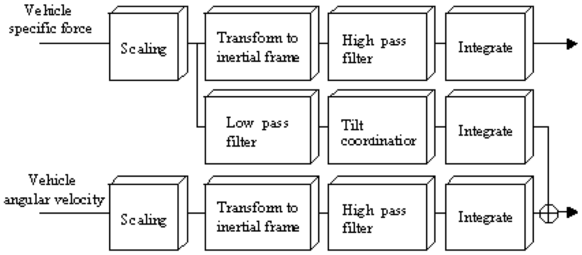

Figure 9: A classical washout filter

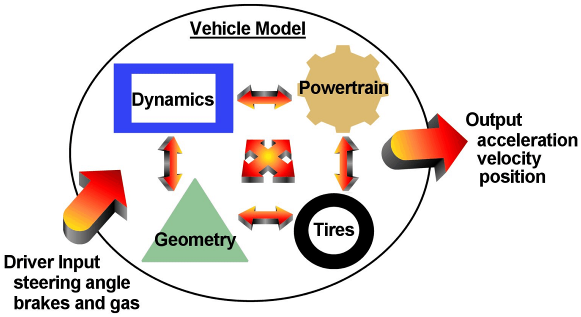

Figure 10: Vehicle model

ing simulated. The training simulator must provide cues that the human receptors interpret as real. Moreover, the simulator must not provide *negative* training. These motion cues must be provided by a combination of environmental prompts and movement of the simulator platform within its operational workspace envelope. They must be imparted such that the perception of the motion and associated forces are sustained while the platform returns, with movement below the perception threshold of the operator, to a neutral kinematic configuration to await the next command input. This is accomplished by a *motion cueing* algorithm, or *washout* filter.

A motion washout filter enforces the physical limits of the constraint envelope of the motion base. Motion cues generated by the washout filter are appropriate if it is in phase with, and scaled in magnitude, compared to the response generated by the vehicle dynamics model [1]. However, false and missing cues can also be caused by the constraint model. A missing cue in the simulator response is a transient vehicle dynamic response completely filtered by the washout algorithm. A false cue can be an expected motion in an unexpected direction, or detectable motion where none should exist. [2].

Hence, the dual objective of the washout filter is to simultaneously maximize the scaling factor of motion cues while minimizing false and missing cues. The *classical washout filter* is shown schematically in Figure 9. Inputs to the washout filter are typically vehicle accelerations, velocities, and orientation, while outputs are configuration commands to the motion base controller. The specific force generated by long duration accelerations can be represented by aligning the gravity vector through a tilting of the motion base: called tilt-coordination [3].

There have been numerous investigations regarding the tilt rate detection threshold level for flight simulators, where the rule of thumb is 3.0 deg/s. However, this is not an accepted threshold value for use in driving simulation, and remains an open question [2].

5.4 Vehicle Model

As discussed previously, an important design objective of SIDFreD is the ability to easily reconfigure the hardware and software to allow simulation of a wide variety of vehicle types. This offers flexibility for research and teaching applications and implies cost-effectiveness through versatility. While multi-functionality underlies the design, and motion specifications were developed considering a variety of vehicle types ranging from fixed- and rotary-wing aircraft, to small marine vehicles, to on- and off-road ground vehicles, it was initially decided to implement a road-vehicle mathematical model on SIDFreD. This decision was influenced by strong research activity at Carleton in vehicle dynamics, road design, and ground transportation; ease of collecting full-scale on-road experimental data; and student experience in operating this vehicle type.

The mathematical model of the vehicle forms the core of the simulation. The vehicle model accepts inputs from the driver (accelerator pedal, brake pedal, and steering wheel) and the simulation operator at the control station (surface conditions and vehicle performance), integrates information from the terrain and road models, evaluates the engine/transmission and vehicle dynamics governing equations, and numerically integrates the governing equations of motion to predict the motion of the simulated vehicle. These calculated motions, in turn, drive the simulation platform washout algorithm and therefore indirectly control the platform motion and provide information to the visual subsystem in terms of where the vehicle is in the virtual environment and what imagery is appropriate for display.

In the first iteration of SIDFreD, a relatively simple open-source road vehicle simulation called CarWorld was used [4]. CarWorld was developed initially as an example code for use in teaching computer programming. Despite a low-fidelity highly-simplified repre-

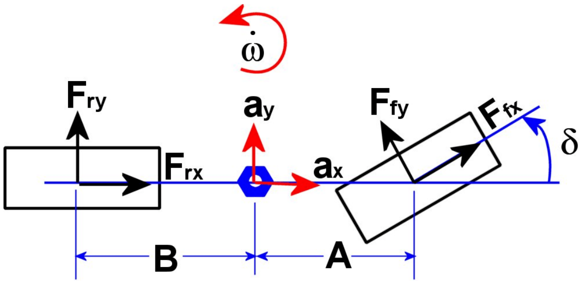

Figure 11: Collapsed tire model

sentation of the vehicle dynamics, CarWorld offered a solid starting point that could be adapted for use with the HLA structure of SIDFreD and that provides the mechanisms for the user interface, graphical display of a road and simple imagery, and evaluation of key vehicle state variables within a single integrated simulation code. CarWorld was effectively expanded and tailored for use with SIDFreD. While an ideal first step, CarWorld lacked the level of vehicle dynamics fidelity and sound engineering approach required for a long-term upgradeable and maintainable solution. It was also too integrated to fully demonstrate the benefits of distributed computing possible through the use of HLA.

As a result, in a second iteration, and engineering-based vehicle dynamics model was implemented. It is based on the classic bicycle vehicle dynamics model. This model collapses the left and right tires on the front and rear axles into two equivalent tires located along the vehicle's geometric centreline, as shown in Figure 11. The model degrees of freedom include the longitudinal and lateral vehicle positions as well as the vehicle orientation relative to an inertial fixed coordinate system. Realistic models of the tire cornering behaviour and combined engine and transmission performance have also been implemented. The user input module from CarWorld was initially retained; image generation was handled using a new dedicated module.

The next iteration of the vehicle model will expand it to three-dimensional motion with four distinct tires and an accurate mathematical modelling of the road vehicle braking system.

6 Application

The SIDFreD platform serves as a test bed for simulation concepts. The ability to analyze concepts, procedures and approaches in the environment in which they are intended to be used provides more accurate results. In addition, familiarization with integrated simulation elements creates a better understanding of a simulation facility.

The three-degree-of-freedom platform is able to operate as a functional multi-vehicle simulator. SIDFreD simulates vehicle motion using a lateral translational platform (1^{st} degree of freedom) to simulate the brief lateral acceleration of the vehicle, and a rotational platform (2^{nd} and 3^{rd} degrees of freedom) to represent the roll and pitch of the vehicle during extended turning, acceleration, and braking.

The design possibilities are infinite, however, the initial implementation was limited to a road vehicle with a rotary-wing aircraft as the second intended vehicle class. This simplified the design, while maintaining the facility's ability to demonstrate the multi-functional possibilities.

7 Future Outlook

SIDFreD's continuing and evolving role at Carleton University can be described chronologically in terms of short, medium, and long time horizons. In the immediate future, SIDFreD will continue to feature prominently as a key element in the CUSP capstone design project as it is a tightly-coupled multi-disciplinary engineering system that offers a multitude of possibilities for student capstone design experience. In the medium term, SIDFreD will be used to support undergraduate and graduate teaching and research in the areas of vehicle dynamics, computer simulation, systems engineering, and robotics. Initial research topics will range from fault tolerance in vehicle electronic stability programs (ESP) through the influence of vehicle/road interaction on road design and vehicle emissions. In the long term, SIDFreD will integrate as a research platform in a larger inter-disciplinary simulation initiative called the Centre for Advanced Studies in Visualization and Simulation (V-SIM) that is currently in the process of being established at Carleton.

8 Acknowledgements

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