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AN APPLICATION SPECIFIC MOTION SIMULATOR DESIGN METHODOLOGY

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Abstract

This paper is part of a research program investigating the systematic, economic optimisation and design of motion simulators, in particular, flight simulators. The research explores reduced actuation motion platforms – primarily three degree of freedom systems (3DOF), as opposed to the traditional six degree of freedom (6DOF) systems. Significant research criteria are cost reduction and reduced actuation mechanism performance optimisation, aimed at eventually realising a more affordable motion simulator solution than those currently available, for commercial application. While reducing cost, the research will attempt to create a performance metric against which proposals can be assessed, leading to a 3DOF solution that maximises performance.

Keywords: design methodology, geometric configuration, commercial application, cost reduction, motion simulation

1. Introduction

Typically, and especially in the training industry, a "flight simulator" has the ability to move in all six degrees of freedom (6DOF) [1] – roll, pitch, yaw, heave, sway and surge, requiring six axis of actuation (Figure 1).

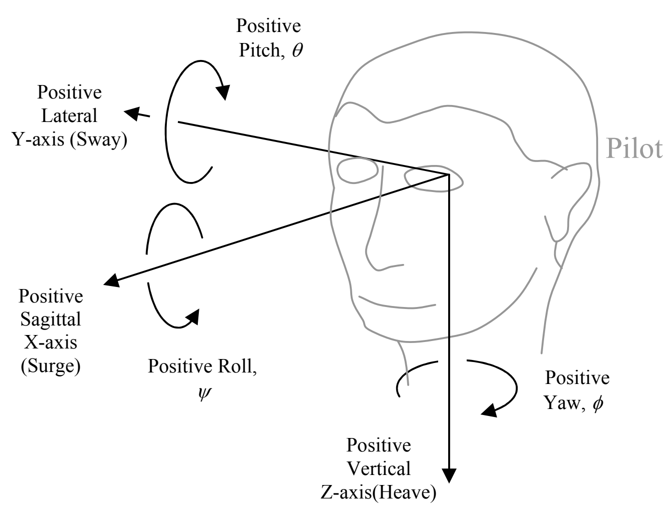

Figure 1 - Coordinate axes convention

The most common geometry for these six-degree of freedom (6DOF) structures is that of a hexapod or Stewart platform [2] as in Figure 3. Due to the complexity of the structure, these motion platforms can be very costly, and difficult to control. It has been shown in the literature that a three axis motion platform (capable only of pitch, roll and heave) can perform quite closely to a six axis machine for the purpose of simulation, and the performance of a three axis machine will be very much dependant on it's geometry for a given application [3]. Thus, the optimisation of three degree of freedom (3DOF) platforms will be investigated and categorised against certain criteria and constraints, with different applications in mind. This optimisation will be the result of a systematic design methodology, which will be developed as part of this research.

The design methodology proposed by this research, to result in an optimised motion platform is briefly outlined in Figure 2.

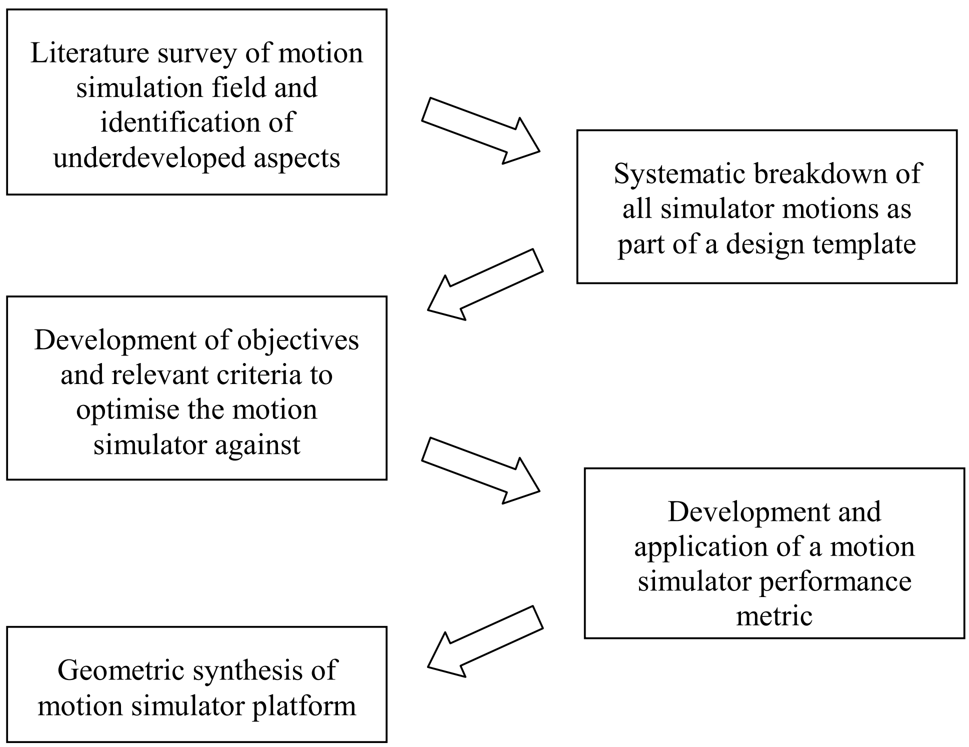

Figure 2 - Optimised motion simulator synthesis design methodology

2. Background

2.1 Six degree of freedom motion platforms

Traditionally, six degree of freedom (6DOF) motion platforms have been the most prominent choice of simulator architecture when it comes to full flight simulation. This is for two main reasons.

1. Motion system accuracy, fidelity, frequency response and weight displacement [2] – a 6 axis system has the ability to independently move in all 6 directions, and hence is theoretically able to attempt to simulate motion in any direction. Most flight industry governing bodies around the world see this as an opportunity for a simulator to be able to

simulate a large percentage of possible aircraft motions, with certain accuracy, and hence specify that a full flight training platform be equipped with 6 axes.

2. Cost of Platform compared to the overall system cost: The motion platform on a full commercial flight simulator will only constitute a small to medium percentage of the total cost of the system. For example, a full flight simulator system operated by QANTAS in Melbourne's flight training centre costs over 20 million Australian dollars, but the motion system under it might only be worth between 1 – 5 million Australian dollars [4]. The remainder of the cost is absorbed by the hardware and software development and design, and the cockpit assembly. A reduction in the cost of the motion system (say to a 3DOF architecture), would not constitute a massive decrease in the overall cost of the system.

Once it is decided that a 6DOF motion system will be used, the next question is usually, "how will the 6 axes be arranged"? There are very many options explored in the literature, from serial actuated to parallel actuated or hybrid systems, from linear extensible members to motor drive geometries, and even some tension only members (as in cable drive actuation) [2]. However, the most highly optimised, mathematically analysed and used 6DOF architecture, according to the literature is by far the Stewart Platform (Figure 3) [1, 2, 5]. This parallel arrangement of 6 extensible members creates a rigid yet versatile system, which can move in all directions with favourable range, speed and force, when compared to its actuator capabilities.

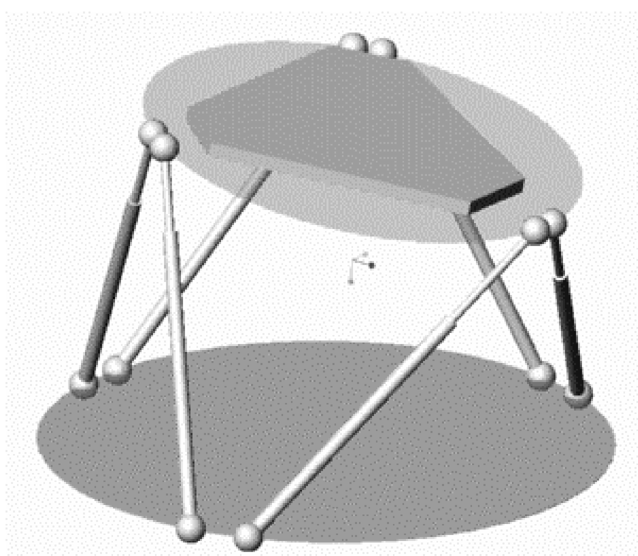

Figure 3 – Schematic of a six axis Stewart Platform

The Stewart Platform is such an optimal method of arranging the 6 actuators that some manufacturers in the past, have concluded that it is easier to design a 6 axes Stewart platform in this way, rather than invest in the design process to create a less expensive reduced actuation systems with 5DOF or 4DOF, due to the associated design and development costs with their inherent risks, and a perceived loss in elegance [6].

These barriers to innovation have resulted in large scale, professional full flight simulation systems having an essentially similar design, with smaller scale systems typically not being economical [6].

Since there is so much commonality in the industry as to the architecture of a flight simulator, a consistent environment for the development of software drive algorithms and washout filters also exists. Most of the washout filter algorithms are designed with the 6DOF architecture in mind [3, 7, 8].

2.2 Reduced actuation motion platforms

All this has resulted in very little work on reduced actuation motion systems, and assessing their capabilities, in comparison to the more common 6DOF systems. What little work has been published, has often demonstrated that the capabilities of such systems, can in most cases be almost indistinguishable from the more expensive 6DOF systems [3]. Many authors have led to the logical conclusion that more research into investigating the performance of cheaper reduced degree of freedom motion platforms for the purpose of simulation is essential. It has been shown that these reduced actuation motion platforms can be designed for a specific application in mind (eg, to simulate a heavy aircraft) and thus resulting in increased performance [3].

3DOF motion platforms are the most prominent reduced DOF platforms in the literature. The most common types are either Heave-Pitch-Roll (HPR) or Pitch-Roll-Yaw (PRY) platforms [3].

- HPR Platforms – Capable of heave motion, pitch motion and roll motion. The most common geometry for these is a parallel actuated arrangement with a sliding platform centroid point constraint, which allows no yaw rotation. The simulator cabin is typically mounted above the platform, resulting in a pitch and roll spin centre well below the occupants' head position. This is the most common 3DOF platform in the literature.
- PRY Platforms – Capable of pitch motion, roll motion and yaw motion. The most common geometry for these is a parallel actuated arrangement with a spherical constraint on the centroid of the platform allowing all rotations, but no linear translation. Once again, the simulator cabin is typically mounted above the platform, resulting in a pitch and roll spin centre well below the occupants' head position.

3DOF platforms mostly have the HPR configuration and usually appear in university laboratories, or as hobbyist's platforms, and not professional flight training systems [4, 6]. Due to the reduced complexity of the platforms, and the reduced amount of actuators and control gear required to make them operate, the cost is kept very low. They are usually teamed up with extremely low priced, yet highly accurate consumer available flight simulation software (such as Microsoft Flight Simulator™) and often provide a very effective, and extremely low cost simulation experience when compared to their full 6DOF commercial counterparts, according to pilot evaluations [9, 10].

These low cost 3DOF simulation systems rarely appear in small to medium flight training schools, or even motor vehicle licence testing and training centres, where they could be of most use to new training pilots or drivers. More often, these training schools and driver training centres prefer to have an office with a desktop computer, and primitive controls for the purpose of simulation, while they prefer that almost all the practical training is performed in the real vehicle, resulting in higher maintenance and tuition costs and occupational health and safety risks [9]. This is due to governing bodies often not acknowledging the validity of most 3DOF motion platforms as accurate simulation environments, since there has not been much research into "measuring" the performance of different simulators [4].

This paper is part of a research program which intends to demonstrate that the many 3DOF systems, when designed in a systematic optimal way, for a given application, and with the correct washout filters, can compare extremely well under most operating conditions to the more expensive and complex 6DOF platforms. The target industry sector of the intended practical application resulting, in part from this research is associated with the operators of small flight training schools, the operators of driving schools, driver test centres and their respective governing bodies.

3. Systematic survey of the scientific literature

Part of the systematic design process for an application specific reduced actuation platform was to determine any design methods already in use, and any potential areas of improvement. A literature review was conducted to learn about the state of the art in motion simulation, and to capture any design methodologies already adopted in the field. The literature review was conducted in a systematic form, presented in part in Figure 4, which was used to identify potential areas of development within the field.

Table 1 – Legend for Table 2

Very High possibility for contribution. May investigate seriously	High possibility for contribution. More information on topic required	Medium possibility for contribution. Should keep in background	Low possibility for contribution. Use literature as reference when needed	Not classified yet, need more research. **If BOLD, then look into ASAP.**

Table 2 – Literature review tabulation and interaction possibilities matrix

Attribute/Research topic	6 axis parallel mechanisms (eg Stuart Platform)	3 axis roll pitch heave parallel mechanism	3 axis general and other platforms	Parallel mechanisms general
Application specific geometric/kinematic configuration design methods	Some work, a paper on optimising workspace for given expected use[14-16]	Not much seen so far. Some mention of possibilities [3, 7, 14-17]	Some general work into how to choose which axis to use [3, 6, 14-17]	Not much material found, but not much effort made into this.
Workspace quantity from configuration, a method of measure?	Lots of papers, but no scientific or mathematical "measure" for workspace proposed	No material found. No way to measure it found either. Some proposals in [17]	Very small amount of limited material. [17, 18]	No generalised method found, but researched effort made
Workspace quality, a method of measure?	Much material, and all based around Jacobian conditioning. Terminology very inconsistent	Very little specific material. Method to measure mostly Jacobian conditioning.	Small amount of data. Method to measure mostly Jacobian conditioning [18]	Little research effort, but much material found. Jacobian conditioning method seems dominant
Mathematical formulation of kinematics	Extremely developed	Several examples [7]	Several examples	Extremely developed.
Singularities of mechanism, methods to quantify? What does the simulator DO near a singularity??	Much material found, but still underdeveloped method of identification, mainly Jacobian c[illegible]nditioning [illegible]	Limited specific material, but still underdeveloped methods of identification, mainly Jacobi[illegible]ditioning	Some specific material, but still underdeveloped methods of identification, mainly Jacobian conditioning	Much material found, but still underdeveloped method of identification, mainly Jacobian conditi[illegible]ning

Figure 4 - Part of systematic literature review survey

The literature survey was fundamental in identifying several key areas within the field which are underdeveloped, and would prove critical in pursuing an optimisation activity on motion simulators. Some of the relevant underdeveloped aspects of the field are outline:

- Application specific geometric/kinematic configuration design methods for 3DOF systems. A method to design a reduced actuation system (3DOF) for a given application and its corresponding data set.
- Workspace quality of 3DOF system. A method to measure the capabilities of a 3DOF architecture (without being application specific), with the workspace quality as a focus.
- Method to measure (modelled) human experience for a given platform, in a given application, and index it, in order to compare against other platforms, eg flying real plane index = 1.0 as a reference point.

- Comparison of Reduced actuation platforms (3DOF) with 6DOF systems, for accuracy of simulation, in a given application. The existence of a performance metric would be required to complete this work.
- Development of algorithms suited to specific kinematic architecture (eg. 3DOF).
- Fidelity in simulation, and how to measure it? Also relates to a performance index for a given simulator, in given application, but fidelity is less application specific, and a more general measure of the simulator's capabilities.
- Method for determining which axis are most important for a given application model. This would aid in choosing which axes to simulate for optimal design approach to produce a lower cost simulator that satisfies the specified performance criteria.

The development of some of these aspects of the simulation field are essential in developing a systematic design methodology, and will be investigated as part of the ongoing research.

4. Simulator motion identification and breakdown

Identifying and isolating the individual motions that a motion simulator may have to perform, and more importantly, the different ways that these separate motions may be created by a specific simulator configuration has been investigated (and shown in part in Appendix I). This work is the starting point for identifying the most important axes that a simulation application may have, and hence allow for designing an optimised simulator for a given application.

The motion isolating investigation also identified possible opportunities to "piggyback" or cross couple certain motions onto other axes. This is illustrated in the following example.

Consider a motion simulator which is only capable of performing a pitch motion (i.e. a rotational motion about the lateral axis – Y-axis in Figure 1). If this spinning motion has its axis of rotation passing through the head of the occupant, then the occupant will only be able to experience the pitching motion (Figure 5) and low frequency surge motion through the use of Coordinated Tilt (Appendix II).

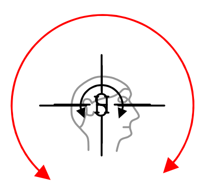

Figure 5 – Pitching motion with spin centre on occupant

However, if the pitch axis is not aligned with the head of the occupant (Figure 6), then the occupant will experience pitching motion, and for small perturbations, at high frequency, the occupant will also experience high frequency heaving motions (i.e. linear motions in the forward and backwards directions – X-axis Figure 1). This means the high frequency heaving motion is cross coupled with the pitching motion, since it is using the pitch axis to enable its occurrence. The cross coupled effect can be highly undesirable in simulation if not accommodated, but this research hopes to exploit this phenomena in order to eliminate the need for some axes, by customising physical configuration for specific applications.

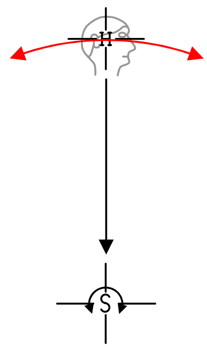

Figure 6 – Pitching motion offset from head resulting in some heave action

This investigation has demonstrated that a key design parameter is the location of the "spin centre" for each rotational axis of simulation. The placement of the spin centre provides an opportunity to add elegance through cross coupling motions. Depending on where the spin centre of certain axes is placed, various results in simulator capabilities arise.

For example, placing the spin centre of pitch or roll below the occupant's head would create a detrimental miscue (or a contradiction in motion) during simulation in a reduced actuation platform. To illustrate:

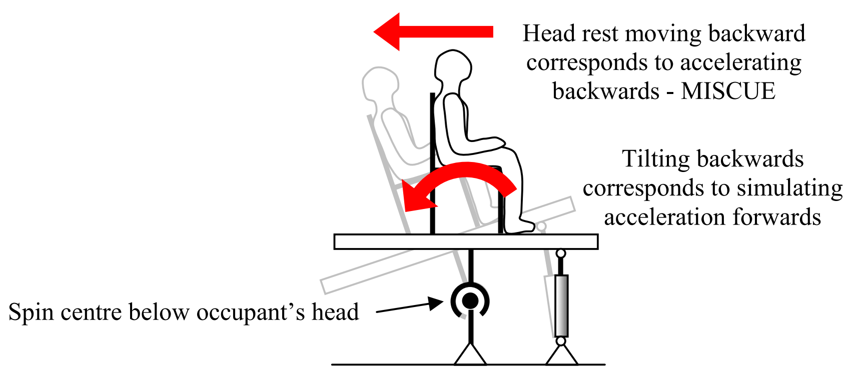

Figure 7 - Miscue resulting from spin centre being below occupant's head

1. The simulator simulates a forward acceleration (surge) experienced by the real vehicle (acceleration in positive X-axis – Figure 1).
2. The washout algorithm accommodates this acceleration by introducing a backward pitch to the occupant (positive angular velocity around the Y-axis – Figure 1) with a spin centre near the feet of the occupant. The linear acceleration will be simulated in Coordinated Tilt (Appendix II). The angular velocity applied by the washout algorithm on the simulator is determined by its control gains. The physical response of the occupant is a reaction force between his back and the seat, as if accelerating forward (positive linear acceleration in X-direction).
3. The simulator reaches an angle which is representative of the linear acceleration to be simulated in Coordinated Tilt. However, since the centre of spin is below the occupant's head, the head experiences a negative linear acceleration in consort with the angular acceleration from the tilting (Figure 7).

4. The occupant experiences a miscue since the simulation sought is where the occupant feels a forward acceleration (i.e. travelling forwards with an increasing velocity), but he feels an instantaneous acceleration backward as the head rest and seat are flung back.

The severity of this scenario is determined by the magnitude of the tilting angular velocity. Although there is negligible miscue when the tilt velocity is low, if this miscue is to be avoided, the associated frequency response of the platform will be severely compromised (Figure 8 (a) and (c)).

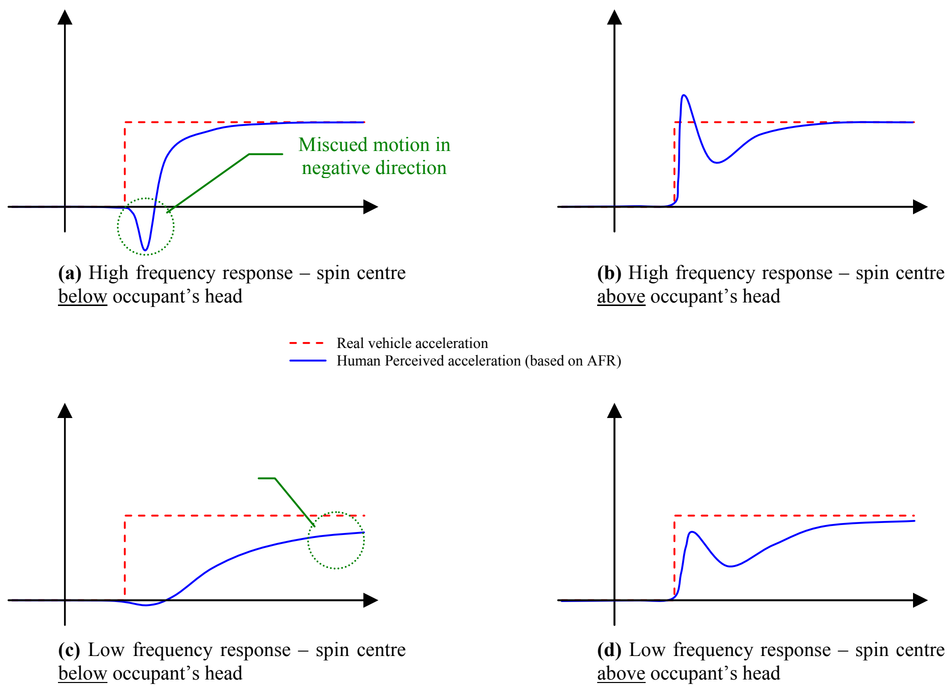

Figure 8 - Human perception of motion with varying spin centre and frequency response

This is why Pouliot, et al found that the addition of a high frequency filter offers little advantage to simulator fidelity, since it would remain unused as the overall simulator design attempts to avoid miscues.

If the same forward acceleration is simulated in a simulator with the spin centre above the occupant's head, then the miscue problem is nullified (Figure 8 (b) and (d)), and the simulator is able to complete both the high frequency and low frequency movements. This analysis has also been completed for the case of sway motion (movement along Y-axis, Figure 1), when coupled with the roll axis, producing identical results.

This motion breakdown investigation will ultimately form the basis for a designer to select which axes are to be simulated and to aid in the systematic synthesis of motion simulator geometry for a specific application.

5. Optimisation objectives for the motion simulator

As is common with any systematic design methodology, a set of objectives (with corresponding criteria) are selected to aid in the design process. This is to prevent the design process from wandering away from the intended product functionality, while also providing parameters to optimise against. A possible set of design objectives, for a particular situation might be those shown in Table 1, with decreasing priority. These objectives would be used to assess any possible design alternatives in a weighted matrix table (weights dependant on designated priorities), in order produce an ultimate winning design which has been optimised.

Table 1 - Motion Platform Design Objectives

Objective	Criteria	Priority
1. **Minimise Cost**	Measured as the aggregate normalised dollar value of designing, constructing and maintaining the motion simulator	1
2. **Maximise Performance Metric Score**	Measured as the "result" from the performance metric (developed in this project), when applied to the simulator	1
3. **Maximise Elegance**	Measured by assessing qualitatively the maximisation of capability while minimising the number of components	2
4. **Maximise Stiffness**	Measured as the deflection the motion simulator physical structure will undergo for a given force applied at various points on the structure, when not in motion	2
5. **Maximise Workspace quantity**	Measured as the movement extremes of the simulator, listed as a set of parameters (eg, pitch capabilities -27^{o} to $+27^{o}$)	3
6. **Minimise Energy Requirement**	Measured as the "energy" required to move the simulator, as a result of its inertia, for a predefined set of simulator moves	4
7. **Minimise Size**	Measured as the size of the structure (volumetric), including all of its workspace quantity	5

These objectives will change, depending on the design philosophy and specific requirements of the application. However, the **Maximise Performance Metric Score** objective (Table 1, Objective 2), is used as a performance measure for the simulator design, and would likely always be included as a design objective for any simulator motion platform. The existence of a performance metric, for the simulation industry is one of the scientific literature short fallings (Section 3), and as such is in need of further investigation. Ongoing research into such a performance metric, to aid in the design process of a motion platform is presented in Section 6.

6. Measuring the performance of a simulator

Measuring the capabilities of a specific motion platform, although seemingly important, is rarely completed in an academic manner in the motion simulation field. In numerous papers, when authors have attempted to access the quality of a simulator, or to complete a comparison of alternate simulator or washout algorithm designs, the prominent method of measurement is an aesthetic assessment of graphical results [2, 5, 11-14]. Typically, "time" will be on the horizontal axis, and quantities such as acceleration or human response (known as afferent firing rate) will be on the vertical axis. The assessment involves highlighting areas of a simulator's response regarded as critical to performance while overlaying graphs of the real vehicle response for comparison. There are however, exceptions where analytical methods have been used to assess the performance of a simulator [3, 10, 15, 16].

With the exception of the methods presented in [10], published findings do not distinguish poor design features in different simulator configurations. For example, the mathematical methods used are based on measuring differences between output responses, (whether it be forces or human response), and as such, they don't penalise different types of miscues more than others, if they have similar deviations from the real vehicle output response. An illustrative example:

A real vehicle moves forward with an acceleration of $0.5 m/s^2$, and a simulator is trying to recreate this. If the simulator instead produces a forward acceleration of $1.5 m/s^2$, the performance metric should penalise the simulator performance, since the simulation is inaccurate. However, if the simulator produces a <u>rearward</u> deceleration of $0.5 m/s^2$, the penalty on the simulator's performance should be more severe. This is due to the fact that, although both responses differ from the desired output response by the same amount ($1 m/s^2$), a human occupant is much more likely to notice a negative acceleration, rather than an acceleration of larger magnitude [17].

Guo et al captures this distinction by default, since pilot performance and behaviour when operating the simulator are used to measure the simulator performance [10]. The method relies on the fact that a pilot will fly an aircraft with more success, if the simulator is accurate in its recreation of the real vehicle. This method of performance measure however, fails to deliver an analytical or mathematical method as it relies on human factors, and hours of human performance testing to develop a result. Many pilots must be tested in order to average out pilot error which is not a result of the simulator's performance.

The current research proposes a method which captures these distinctions, by applying different penalty weights to different response anomalies, while using human models to measure the deviations in response between the real system and the simulation. As [3] shows, using human based models, with their inherit damping effects, reduces the need for extremely high fidelity motion systems to perform well in simulation. Lahiri further questions the need for high fidelity, observing that historically, the use of expensive, high fidelity systems are due to the fact that most previous analytical performance assessment has been based on measuring mathematical quantities (such as specific forces) that the simulator produces, instead of assessing the effects the simulators have on the human occupant [18]. This disregards the damping effects of the vestibular system, resulting in the need for high fidelity to make the mathematical quantities of the simulation as close as possible to the real vehicle.

The performance metric from this research would measure the ability of a simulator to recreate a specific real vehicle's motion, and produce a score for that simulator-vehicle combination, which could be compared against other simulator-vehicle combination scores, and hence offer a criteria for measuring the performance objective. The performance metric would be a mathematical method, incorporating the human models of response to motion. There would also be an accompanying rule set, which specifies the conditions of applying the performance metric (eg. How representative the simulation data must be of typical use of the real vehicle – or completeness of data, which is used in testing the performance of the simulator).

The literature contains a great deal of information about what a human being "feels" when subject to motion, and many authors have proposed various "human models", or mathematical transfer functions which may be used to convert the real world accelerations to a quantifiable internal human "signal". Typically, these models describe their output as Afferent Firing Rate (AFR), the magnitude of signal sent to the brain by the acceleration sensors in the inner ear (and other body sensors), under a given acceleration. This forms a convenient method to model the human experience of a given simulator motion, while not using human subjects.

The factors which affect "human experience", or AFR in the simulation environment, have been considered, and various aspects of motion, which are known to detract from the simulation experience, have been identified in the literature. The factors which the performance metric function will consider (and penalise) are:

Factor-1: Deviation of the simulation AFR data from the real vehicle occupant AFR data in the same direction. An occupant in a simulator feels like he is accelerating mildly, while in reality he is supposed to feel high acceleration as in the real vehicle. The associated performance metric factor would introduce a medium penalty rate (on the performance of the simulator-vehicle combination), since the inner ear is not a calibrated instrument (eg. in comparison to a digital accelerometer), and cannot easily distinguish between levels of experience very well. To illustrate this, most humans cannot say with a high degree of certainty, whether they are accelerating at $1.6 m/s^2$ or $1.9 m/s^2$ when being accelerated, but they can easily determine if they are accelerating forwards, or backwards [1, 5].

Factor-2: Deviation of the simulation AFR data from the real vehicle occupant AFR data in the opposite direction. An occupant in a simulator experiencing acceleration, while in reality he is supposed to feel a deceleration as in the real vehicle. This factor would also include if the simulator is moving when not supposed to, and not moving when supposed to. The associated performance metric factor would introduce a high penalty rate, since humans can determine if they are accelerating or decelerating quite easily, and this phenomenon is the main culprit for occupants feeling "motion sickness" in simulators and rides [1, 5].

Factor-3: Deviations of simulation AFR gradient from real vehicle AFR gradient in opposite direction. An occupant feeling like they are increasing their acceleration in the simulator (positive *jerk*), while they are supposed to be decreasing their acceleration as in the real vehicle (negative *jerk*). This would most likely carry a high penalty, since humans can determine direction of acceleration increase (*jerk*) easily, using the sensors in the inner ear [1, 5, 16].

Factor-4: Deviations of simulation AFR gradient from real vehicle AFR gradient in same direction. An occupant in a simulator feeling like they are slowly increasing acceleration (small *jerk*), when in actual fact they are supposed to be increasing acceleration rapidly as in the real vehicle (large *jerk*). This would most likely carry a low penalty, since the inner ear is not a calibrated instrument, and cannot easily quantify at what rate an acceleration is increasing [1, 5].

Factor-5: Shifting focus of occupant to more dominant axes. If certain axes generate less AFR signal during simulation, because other axes are being excited more heavily, the penalty rate associated with the less dominant axes should decrease, since the human occupant is "distracted" by the dominant axes, and is less likely to notice inaccuracies in the simulation experience in the less dominant axes [5].

This is an interim list only, as it is expected that the relative merits of these factors will be understood, and the discovery of additional factors will occur, as the research evolves.

The influences of Factor-1 to Factor-4 are identified in Figure 9. Each Factor is not exclusive, and various types of deviations are likely to occur simultaneously.

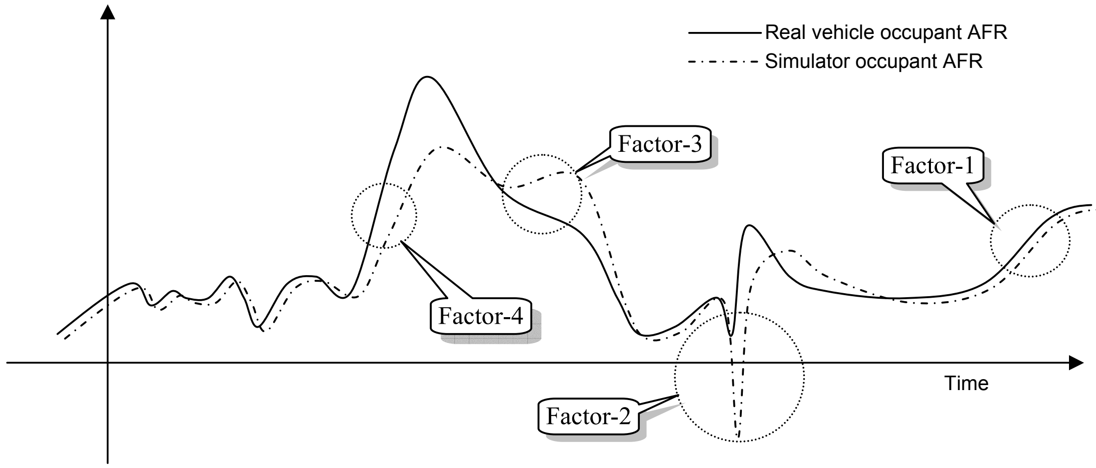

Figure 9 – Schematic of various examples of simulator and real vehicle AFR inconsistencies.

Time lag, or delay in the motion cues, is also a traditional cause of occupant motion sickness during simulation motions. A performance metric which considers all the above separately however, will by default also consider time lag, since time lag is the catalyst by which all of the above points become prominent. Time lag causes the simulator occupant AFR signals to shift forward in time (relative to control inputs) compared to the real vehicle occupant AFR, resulting in more difference between the two graphs.

Currently, the performance metric for a simulator in this research is described in equation (1), and has the form of a cost function. The lower the result, the better the match between the simulator and the real vehicle (i.e. the real vehicle scores zero under this metric system, when combined with its own data).

The cost function, for the i^{th} axis, is:

$$C_i = C_{1i} + C_{2i} + C_{3i} + C_{4i} \tag{1}$$

where,

$$C_{1i} = w_{1i} \cdot \left| \frac{AFR_{i_{real}} - AFR_{i_{sim}}}{AFR_{i_{real}}} \right| \cdot \left| \frac{\operatorname{sign}\left(AFR_{i_{real}} \cdot AFR_{i_{sim}}\right) + 1}{2} \right| \tag{2}$$

$$C_{2i} = w_{2i} \cdot \left| \frac{AFR_{i_{real}} - AFR_{i_{sim}}}{AFR_{i_{real}}} \right| \cdot \left| \frac{\operatorname{sign}\left(AFR_{i_{real}} \cdot AFR_{i_{sim}}\right) - 1}{2} \right| \tag{3}$$

$$C_{3i} = w_{3i} \cdot \left| \frac{\frac{d}{dt}\left(AFR_{i_{real}}\right) - \frac{d}{dt}\left(AFR_{i_{sim}}\right)}{\frac{d}{dt}\left(AFR_{i_{real}}\right)} \right| \cdot \left| \frac{\operatorname{sign}\left(\frac{d}{dt}\left(AFR_{i_{real}}\right) \cdot \frac{d}{dt}\left(AFR_{i_{sim}}\right)\right) + 1}{2} \right| \tag{4}$$

$$C_{4i} = w_{4i} \cdot \left| \frac{\frac{d}{dt}\left(AFR_{i_{real}}\right) - \frac{d}{dt}\left(AFR_{i_{sim}}\right)}{\frac{d}{dt}\left(AFR_{i_{real}}\right)} \right| \cdot \left| \frac{\operatorname{sign}\left(\frac{d}{dt}\left(AFR_{i_{real}}\right) \cdot \frac{d}{dt}\left(AFR_{i_{sim}}\right)\right) - 1}{2} \right| \quad (5)$$

The parameters w_{ni} are conceptual weights, which affect the penalty associated with each factor, and are being investigated as part of this research.

There are significant uncertainties associated with this cost function, including how it can be successfully applied, and the appropriate input data to maximise the certainty of a meaningful performance measure. Preliminary trials however, have shown it to be a useful measure for analysing results from other parts of the research, such as the optimisation of the 3DOF platform

7. Case study: Early design of a 3DOF platform for light aircraft

As an implementation of the proposed simulator design methodology, work has begun on the design for an application specific reduced actuation (3DOF) motion platform for the purpose of simulating a light aircraft.

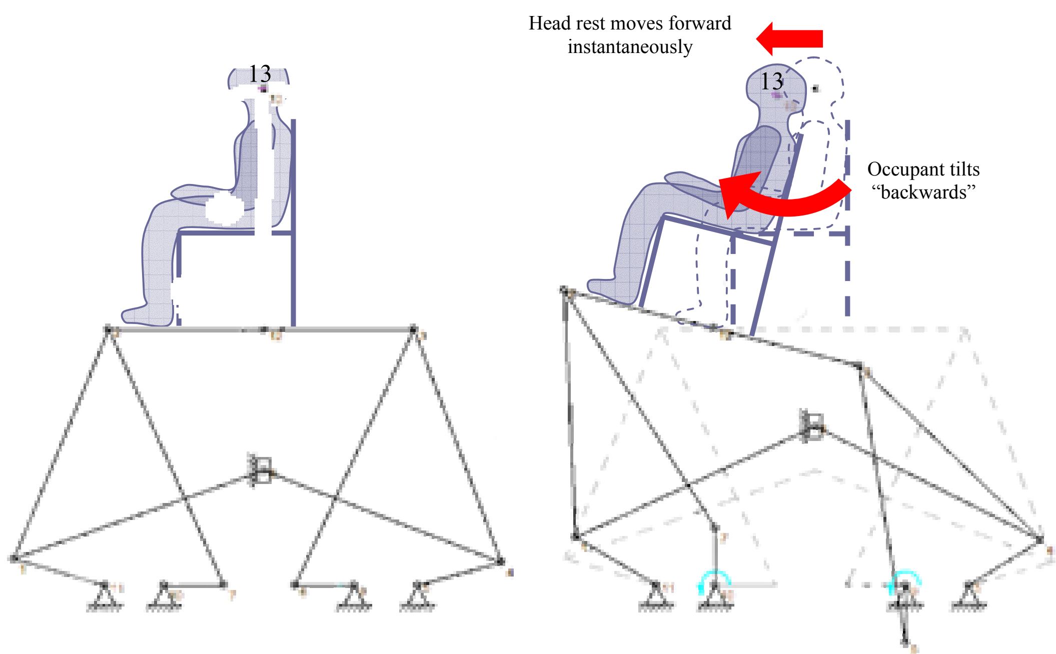

Figure 10 – (a) The simulator at central position and (b) moving to simulate a forward acceleration on occupant

Following analysis of the real vehicle data and use of the simulator motion breakdown investigation, a 3DOF motion platform employing pitch, roll and heave as the primary axes was selected. This investigation has begun with attempts to generate ideas for the synthesis of the geometric configuration, to take into account the fact that a small aircraft will have many high frequency motions due to its light weight, meaning that the placement of the spin centre of the pitch and roll axes will be critical.

It has been decided, by use of the conceptual tools developed in this research, that the spin centres of pitch and roll should be above the pilot's head, and several alternative geometric configurations have been developed to allow for this. One of these is shown in Figure 10

This mechanism, although shown only in 2 dimensions, is to be generalised into 3 dimensions. A snapshot of its motion is shown in Figure 10 (a) and (b).

8. Conclusions

The following conclusions have been made as a result of the research to date.

- The simulation industry can benefit from the design and development of reduced actuation simulator motion platforms, which are optimised through systematic design methodologies to perform well in specific applications. Though still in the early stages of this research, the case study demonstrates how an optimised design process may aid in capturing extra functionality and reduce unwanted aspects of the simulation, through elegant planning of the geometric configuration.
- A systematic design methodology or toolkit (such as the one presented in this work) for simulation motion platforms would enable a simulator designer to optimise the process of creating a motion platform specific to an intended application.
- The need for a generalised analytical performance metric for motion simulators is essential for the industry. The performance metric should be designed such that it will penalise a simulator's performance based on factors which a human can detect, not necessarily physical quantities such as acceleration. The performance metric should differentiate between different types of performance inadequacies.
- Further research into developing a systematic method for designing the washout filters or drive algorithms for a reduced actuation motion platform must be made. Most of the current algorithms are based on existing 6DOF algorithms, which may not be well suited, or take advantage of a specific reduced actuation motion platform.

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Appendix I – Extract from the Motion Recreation Matrix

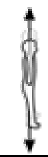
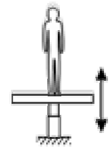
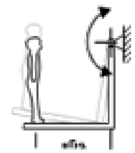
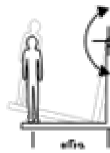
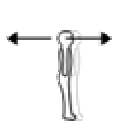
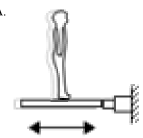
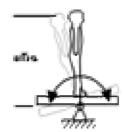
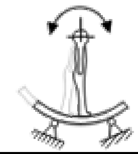
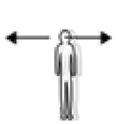
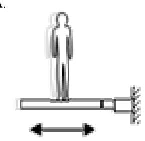
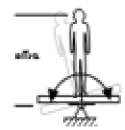
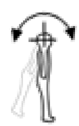
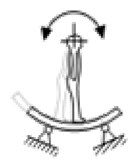
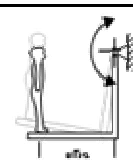
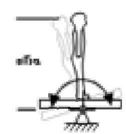
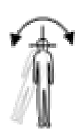
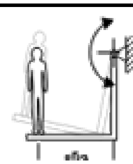
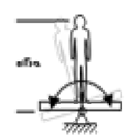
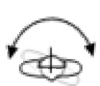
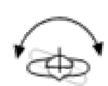
Real motion description	Simulation possibilities to recreate real motion		
Heave Linear motion in the up/down direction. Axis through head 	**True Heave Axis** Very Good in High F, small A. Need "long" axis for low F and large A 	**Horizontally Offset Pitch Axis** Good in High F, Small A, but coupled with Pitch Axis. Lose effect as F decreases and A increases. Offset determines effect, but also damages Pitch axis. 	**Horizontally Offset Roll Axis** Good in High F, Small A, but coupled with Roll Axis. Lose effect as F decreases and A increases. Offset determines effect, but also damages Roll axis. 
Surge Linear motion in the forward/back direction. Axis through head 	**True Surge Axis** Very Good in High F, small A. Need "long" axis for low F and large A 	**Vertical Offset Pitch Axis** Good in High F, Small A, but coupled with Pitch Axis. Use "co-ordinated" tilt as F decreases and A increases, makes this favourite for "long" surges. Offset determines effect, but also damages Pitch axis. 	**True Pitch Axis** Very Poor in High F, small A. Very Good for low F and large A, using tilt co-ordination. Coupled with Pitch axis though. 
Sway Linear motion in the left/right direction. Axis through head 	**True Sway Axis** Very Good in High F, small A. Need "long" axis for low F and large A 	**Vertical Offset Roll Axis** Good in High F, Small A, but coupled with Roll Axis. Use "co-ordinated" tilt as F decreases and A increases, makes this favourite for "long" sways. Offset determines effect, but also damages Roll axis. 	**True Roll Axis** Very Poor in High F, small A. Very Good for low F and large A, using tilt co-ordination. Coupled with Roll axis though. 
Pitch Rotational motion in the tilt forward/back direction. Centre of spin at centre of head 	**True Pitch Axis** Very Good in High F, small A. Need "long" axis for low F and large A. Coupled with co-ordinated tilt of Surge axis 	**Horizontally Offset Pitch Axis** Bad in High F, Small A, and coupled with Heave Axis. Gets better as F decreases and A increases. Offset has detrimental effect on Pitch, and couples it more with Heave. 	**Vertical Offset Pitch Axis** Bad in High F, Small A, and coupled with Surge Axis. Gets better as F decreases and A increases. Offset has detrimental effect on Pitch, and couples it more with Surge. 
Roll Rotational motion in the tilt left/right direction. Centre of spin at centre of head 	**True Roll Axis** Very Good in High F, small A. Need "long" axis for low F and large A. Coupled with co-ordinated tilt of Sway axis 	**Horizontally Offset Roll Axis** Bad in High F, Small A, and coupled with Heave Axis. Gets better as F decreases and A increases. Offset has detrimental effect on Roll, and couples it more with Heave. 	**Vertical Offset Roll Axis** Bad in High F, Small A, and coupled with Sway Axis. Gets better as F decreases and A increases. Offset has detrimental effect on Roll, and couples it more with Sway. 
Yaw Rotational motion around the up/down axis. Centre of spin at centre of head 	**True Yaw Axis** The only way available to simulate Yaw. Thus for High F, low A, 100% and Low F, High A, 100%. No other options are available if Yaw is important to the simulation effect. 		

Figure A1 – Extract from the Motion Recreation Matrix

Appendix II – Description of Coordinated Tilt

The idea is to tilt the occupant of the simulator in such a way as to use the gravity reaction at an angle to fool the occupant into thinking they are accelerating in another direction. Co-ordinated Tilt is most effective for long, low frequency motions, since the simulator can sustain them by remaining in a tilted position for long periods of time.

There is a theoretical limit to how large a magnitude inertial acceleration can be simulated by Coordinated Tilt, since it uses the gravity vector to simulate the inertial acceleration. The theoretical limit is $1g$, when the simulator is at a tilt angle of 90^o, but this has certain drawbacks, since there is no "gravity" vector felt by the occupant anymore. This doesn't "feel" like 1g forwards anymore, since there is no reaction felt by the seat in the –ve Z axis relative to the head of the occupant.

To illustrate, real vehicle begins to accelerate forwards at $1.1 m/s^2$. So, to simulate, the drive algorithms begin tilting the simulator cabin to 6.43^o in positive pitch direction (i.e., tilt head backwards). However, depending on how "fast" this acceleration was built up to $1.1 m/s^2$ in the real vehicle will determine how accurately it can be reproduced in the simulator without affecting other sensors. This is because when the simulator tilts the occupant, it can't apply the tilt too quickly, because the occupant will "feel" a rotation, which the original vehicle did not perform. Thus, there will be a false cue. Co-ordinated tilt is generally used to simulate low frequency (or long), low amplitude motions.

Eg. To simulate $1.1 m/s^2$ in surge (positive X direction)…

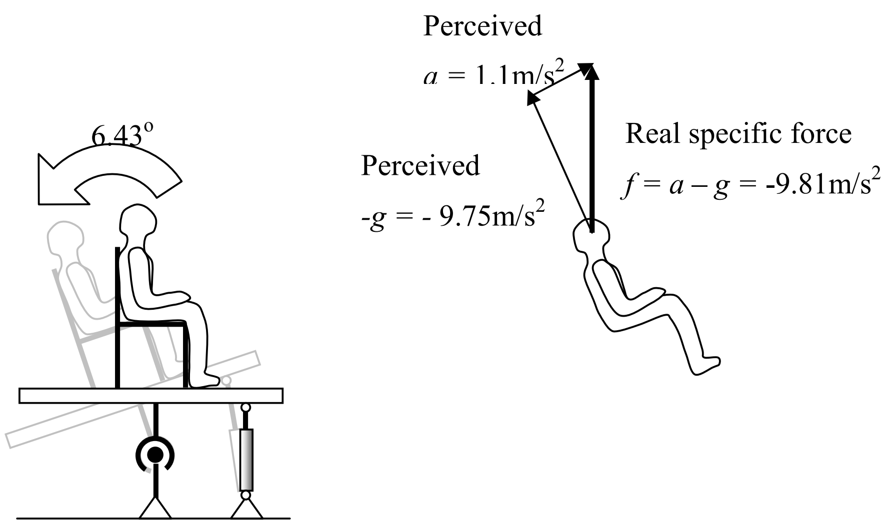


Figure A2 – Coordinated Tilt schematic