Simulating Motion Effects Using a Hydraulic Platform with Six Degrees of Freedom

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ABSTRACT
The simulation of motion effects adds another dimension to the simulation process, thus significantly enhancing its authenticity. This paper describes the simulation of motion effects via a hydraulic base with six degrees of freedom. It provides a kinematic description of the hydraulic base and explains the motion effect controlling concept. We shall also present an actual implementation of the concept discussed herein which is used as an IFV simulator by the armed forces of the Czech Republic.

KEYWORDS
Stewart platform, hydraulic platform, virtual reality, simulation, simulator.

1. Introduction

A simulator is a device reproducing, as accurately as possible, the characteristics of real devices such as airplanes and vehicles. Simulators are often used for pilot and driver training. Involving a simulator in the training process has two main benefits: First, the driver's or pilot's mistakes made during the simulation do not jeopardize his health. The second benefit is an economic one – it is much cheaper to operate a simulator than the real device.
The simulation of motion effects increases the authenticity of the simulation process, thus playing an important role in particular in the case of vehicle and plane simulators, where the forces acting on the driver / pilot play a significant role and influence his actions. In fact, it is safe to say that vehicle and plane simulators without motion effect simulation features can do more harm than good, with the trainee potentially learning bad habits.
In simulation technology, a platform with six degrees of freedom (or Stewart Platform, as it is commonly called in technical literature) is typically used for this purpose today. However, the extent of movement of this device being limited, it necessary to take these restrictions into consideration by integrating so-called 'washout filters' into the simulation algorithm.

2. Vehicle Simulators

Despite there being many different simulator types, the underlying logic of the simulation algorithm is generally characterized by Fig. 1. As it is envisaged to use the concept presented in this paper for vehicle simulators in the first place, we shall focus specifically on this area. However, the same principles can be applied to plane simulators as well.

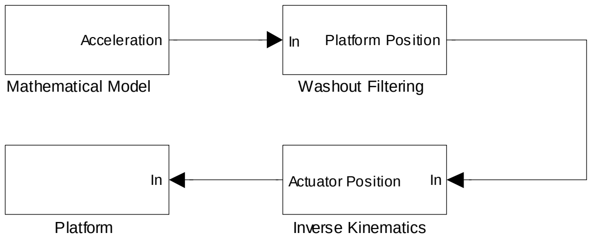

Fig. 1: Simulation process flowchart

The core of the simulator is a mathematical model of the reproduced vehicle. The accuracy of this model determines the overall simulation quality. The mathematical model calculates the responses of the simulator to the driver's actions. The resulting dynamics is transformed as an acceleration vector on the position of the base and individual actuators.

3. Hydraulic Platform

Equipped with the necessary audiovisual systems and controls, simulators are typically very heavy. For instance the weight of the IFV simulator presented later herein is about 1.5 tonnes. Hence the actuators of the platform have been implemented as hydraulic cylinders, this solution ensuring high dynamics and overall system reliability. Moreover, compared to electric systems providing the same performance, the price of hydraulic systems is considerably lower. The structure of the six-degree-of-freedom base is shown in Fig. 2.

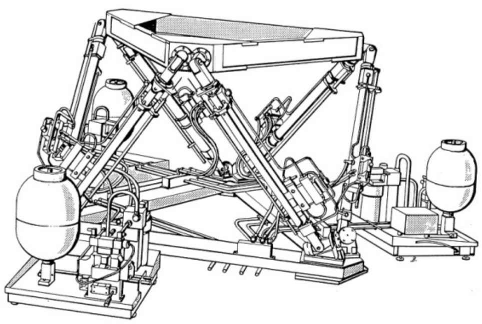

Fig. 2: Hydraulic base with six degrees of freedom

The base is a parallel manipulator (widely referred to as a Stewart platform in technical literature) capable of moving in all six basic directions (3 linear and 3 rotational directions).

4. Inverse Kinematic Algorithm

The mechanical system shown in Fig. 2 is made of six hydraulic cylinders attached to a pair of frames: a lower (fixed) and upper (movable) frame. We shall define two frames of reference – a fixed one (referred to as O_1) having its beginning in the centre of the lower frame, with the X and Y axes being level with the lower frame and the Z axis parallel to the gravity vector, and a movable one (referred to as O_2) positioned in the same way at the upper frame. Therefore, when the manipulator is idle and all cylinders are in their starting positions, both frames of reference are only shifted along the axis Z, the planes defined by the axes X and Y of the reference frames being parallel. Now we can define the six possible movement types. The upper (movable) frame of reference can rotate, with respect to the lower (fixed) system along the axes X, Y and Z. These angles shall be called ϑ, φ and ψ respectively. Further, the upper frame of reference can move in the direction of the X, Y and Z axes. These movements shall be called ΔX, ΔY and ΔZ. Assuming the mutual position of both frames of reference is known, the generic point $\mathbf{x}_{O2} = [x, y, z]^T$ expressed in the reference frame O_2 can be transformed to the reference frame O_1 with the following relationship:

$$x_{O1} = R \cdot x_{O2} + p, \qquad (1)$$

where R is the rotation matrix (3x3) depending on the angles ϑ, φ and ψ and $\boldsymbol{p}$ is a vector in the following form:

$$p = \begin{pmatrix} \Delta X & \Delta Y & \Delta Z - Z_0 \end{pmatrix}^T, \qquad (2)$$

Z_0 being the initial (idle) difference in position of the two frames of reference with respect to each other. Using homogenous coordinates the rotation matrix and the shift vector can be merged into one transformation matrix T (4x4) and equation (1) can be rewritten as follows:

$$x_{O1} = T \cdot x_{O2}, \qquad (3)$$

where T is the matrix in the form:

$$T = \begin{bmatrix} R & p \\ 0 & 1 \end{bmatrix} \qquad (4)$$

and the generic point **x** is expressed as:

$$x = [x, y, z, 1]^T. \qquad (5)$$

Knowing the geometry of the base, we can express the coordinates of the position of the upper cylinder endings with respect to the reference frame O_2. Subsequently, we can transform these points to the reference frame O_1 using the relationships (1) and (3). In this reference frame, we determine the coordinates of the lower cylinder endings. Using the distance between these two coordinates (i.e. the lower and upper cylinder ending) we can determine the necessary displacement of the piston. Therefore, the equation expressing the displacement of one of the pistons of the base can be written as:

$$v = \left| T \cdot x_{O2}^{h} - x_{O1}^{d} \right| - v_0, \qquad (6)$$

where T is the transformation matrix, v_0 the length of the cylinder with the piston in its idle position, $\mathbf{x}_{O2}^{h}$ the position of the upper cylinder ending in the reference frame O_2 and $\mathbf{x}_{O1}^{d}$ the position of the bottom cylinder ending in the reference frame O_1.

5. Motion Effects Simulation Algorithm

The simulation of motion effects is based on the basic principle of dynamics: When in accelerated motion, a body is affected by inertial forces acting in a direction opposite to the direction of acceleration. According to Newton's laws, this force is proportional to the mass and acceleration of the body acted upon.

As already pointed out before, the range the hydraulic platform presented hereinabove can move in one direction is limited, the maximum distance along each axis being about 30 cm. This linear movement alone allows only the simulation of short-term acceleration. When longer acceleration is required, linear motion has to be supplemented with appropriate rotary motion. The nature of the human vestibular system makes it impossible for us to distinguish between the feelings we experience when subject to acceleration and the situation when the simulator cockpit is turned by a specific angle. This situation is shown in Fig. 3. The driver is under the effect of a gravitational force characterized by the gravitational acceleration ***g***. In addition, the driver is also under the effect of the inertial force ***a*** (the figure shows the scenario when the vehicle is slowing down). The driver feels the acceleration ***k***. Assuming $|a| << |g|$ the following relationship holds true $|k| \approx |g|$, meaning that the result is the same when the cockpit is turned by the angle φ (see Fig. 3). Mathematically, the last statement can be expressed with the following formula:

$$j = \arcsin\left(\frac{a}{g}\right). \tag{7}$$

The previous assumption is approximately true for accelerations up 5 m/s^2. In this case, the relevant angle is φ = 30°.

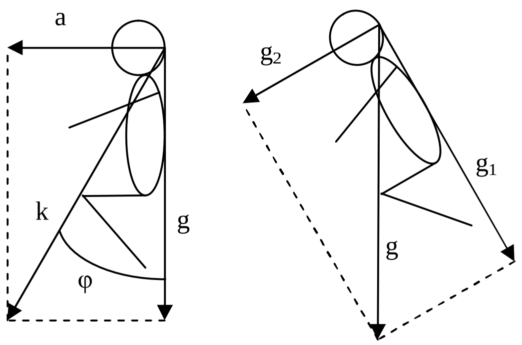

Fig. 3: Simulating linear acceleration by tilting the base.

However, this rotation has to be slow enough (ideally beneath the human threshold of perception) to make sure that the person in the cockpit does not really perceive the movement of the base.

The whole transformation algorithm is shown in Fig. 4. The acceleration vector obtained via the mathematical model is split by a frequency filter into high-frequency and low-frequency acceleration. Based on empirical research, the boundary between the low-frequency and high-frequency parts has been set to 0.5 Hz. Low-frequency acceleration is transformed, via the above algorithm, on the rotary position of the base and added to the current rotary position of the simulator. The double-integral of the high-frequency acceleration is transformed on the linear position of the hydraulic base. However, this movement being very limited, as already pointed out herein, so-called 'washout filters' have to be applied in this part of the algorithm to continually reset the position of the base in a way not perceptible to human senses. Washout filters can be implemented in a number of different ways. We shall describe here a method based on the theory of dynamic systems.

The Laplace image of the transfer function of the high-frequency part comprising of two integrators has the following form:

$$G_h(s) = \frac{1}{s^2}. \tag{8}$$

We can now extend the system with a status feedback to make sure the resulting system is stable. As another requirement, the transition characteristics have to be without overshoot and the resetting movement to the initial position must not exceed the human threshold of perception. Let us therefore set the status feedback in a way to ensure that the resulting transfer has one double real root lying in the negative half plane of the complex plane:

$$G_h(s) = \frac{1}{(s - l)^2} = \frac{1}{s^2 - 2sl + l^2}. \tag{9}$$

Filtration speed is determined by the position of the pole λ on the real axis, the latter being defined empirically when implementing the algorithm. The lower is the pole, the faster the filtration will be.

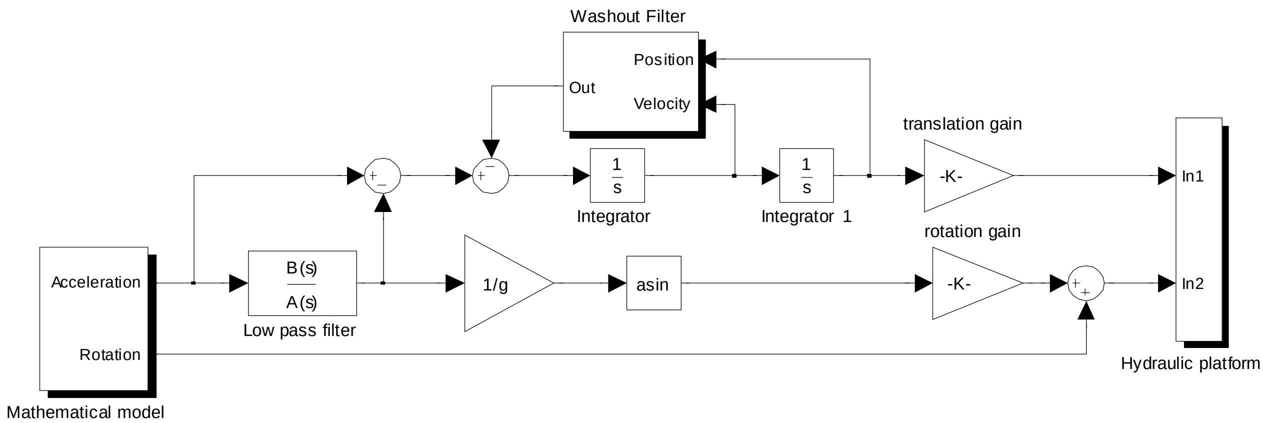

Fig. 4: Motion effects simulation algorithm

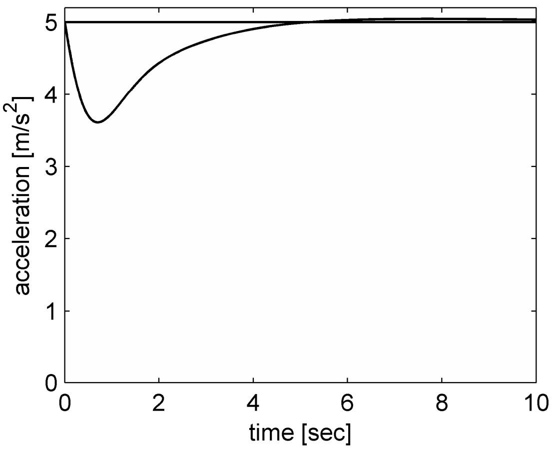

Fig. 5: Simulated and real acceleration

Figure 5 shows the reaction of the algorithm to an immediate increase in acceleration. The gradual decrease in acceleration is caused by the limited possibilities of linear movement.

6. IFV Simulator

Figure 6 shows an implementation of an infantry fighting vehicle (IFV) simulator. This device utilizes the algorithms described in this paper and is currently being put into operation in Czech armed forces.

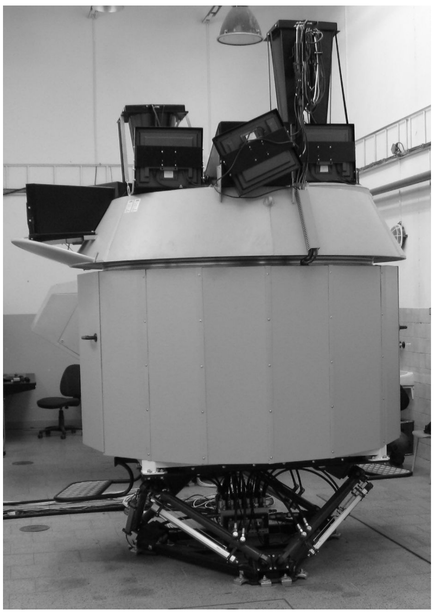

Fig. 6: IFV simulator

The development stage of the simulator has already been completed. By the end of 2008, the army envisages to put four simulators into operation and make them available for driver training.

7. Conclusion

This paper describes the motion effect simulation algorithm used in the implementation of an IFV simulator for the Czech army. The first prototype of the simulator has already been approved by the Army's expert committee and is being used for driver training.
As of today, development is focused mainly on measuring the dynamic properties of the hydraulic base and validating the feelings experienced during the simulation process.

Acknowledgements

I would like to express my thanks to Pragolet, s.r.o., a specialized designer and manufacturer of hydraulic bases, which has been taking an active role in developing the simulator described herein.

References

[1] E. Thöndel, Hydraulic platform as a device for simulation of acting forces in flight and driver simulators. *Proc. International Conf. on Radioelektronika, elektrotechnika i energetika*, Moscow, Russia, 2007, 425-426.

[2] E. Thöndel, Hydraulická základna jako prostředek pro simulaci sil v leteckých a řidičských simulátorech. *Proc. International Conf. on Kateder částí a mechanismů strojů*, Liberec, Czech Republic, 2005, 341-244.

[3] Z. Šika, P. Beneš, M. Valášek, New washout algorithms for driving simulator, *International Journal of Engineering Mechanics, 12*(4), 2005, 259-266.

[4] E. Thöndel, *Simulace pohybových vjemů na pilotním trenažéru* (Dissertation, 1981).

[5] Pragolet, s.r.o. *Pragolet, s.r.o.* [Online]. [quot. 17/04/2008] <http://www.pragolet.cz>.