On the Problem of Synchronization of Virtual and Real Movements for Virtual Reality Systems

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Abstract. An immersive experience in modern virtual reality systems requires adjusting of various parameters. This report focuses on the problem of virtual representation of real movements of objects in space. Separately, a special class of problems is highlighted: synchronization of visual and dynamic imitation for virtual reality systems and motion platforms. Modern mass-produced virtual reality headsets do not allow effective tracking of human movements on a moving base using standard software. The element base and algorithms necessary for the successful solution of this problem are presented.

1. Introduction

The creation of dynamic and visual simulators to simulate various processes has made it possible to create different training systems. Simulators are designed for tasks often associated with high costs in case of erroneous actions and for simulating emergencies.

One of the spheres of human activity that requires special training is in-flight work conditions. For example, training on flight simulators is one of the integral parts of training for passenger aviation pilots worldwide. The conditions of aircraft flight and microgravity observed during an orbital flight are unusual for humans. Therefore, any action in flight can cause difficulties for an unprepared person, which means that specific training should be performed.

Modern systems based on virtual reality (VR) technology are designed to learn and repeat various flight modes and provide simulations of both standard and complex flight modes. An essential feature of such systems is the coincidence of the supplied simulation with the actual situation. In particular, in-flight simulators, visualization, and motion stands (for example, the Stewart platform) are used together. Any discrepancy can lead to impairments, in particular, the development of motion sickness. When developing a new type of stand based on a manipulator arm and virtual reality headsets, the task becomes even more difficult due to the high mobility of both the stand and the helmet. To reduce the negative effects of virtual simulation, it is required to solve the problem of synchronizing visual and dynamic simulation, the approach to which is described in this paper.

2. The Structure of the Problem of Synchronization of Virtual and Real Movements

2.1. Reasons of signal desynchronization

The vestibular apparatus is connected through the shortest three-neuron chain in the body with the oculomotor muscles. The eyes' reaction to rotation occurs reflexively, bypassing the higher structures
of the central nervous system. The compensatory movement of the eye relative to the movement of the head is called the vestibular-ocular reflex (VOR). When fixing the gaze on the head's point and passive turns thanks to the VOR, a clear vision is maintained. In virtual reality conditions, the information from the vestibular sensor does not always coincide with the supplied image. Because of this, the mechanism of the vestibular-ocular reflex is disrupted, and motion sickness, also called exercise sickness, can occur, one of the symptoms of which is motion sickness.

The correctness of the perception of virtual reality critically depends on the synchronization of the reproduced imitation and actual human actions. To allow the user to correctly perceive and interact with virtual objects in real time, it is required to receive up-to-date information about the position of his head and limbs. Let us introduce the concept of a virtual screen - an object located at a certain distance in front of a virtual eye camera. We assume that the distance is known and depends on the design of the visualization system. The virtual screen must match the real screen in aspect ratio and angular size. However, it may be closer to the virtual eye than the real screen to the real eye.

A significant amount of virtual reality simulation programs are designed for small relative movements of the user. So, for example, in most training systems designed to simulate aerospace flights, the pilot is assumed to be strapped to the seat [1]. When the screen of the visualization system is stationary relative to the platform, this assumption allows us to build the visualization in advance in the form of a static transformation between the virtual camera and the position of the eye.

However, in modern systems with a split-screen from the platform or in systems based on a virtual reality helmet, the transformation becomes dependent on the dynamics of the platform and the pilot's head. As a result, it becomes necessary to use specialized tracking systems to track the rotation of the user's head. Usually, video analysis is used for these purposes [2]; hybrid motion tracking methods have also been proposed. Experiments on the panoramic virtual reality system of Moscow State University have shown that even when using expensive video analysis systems, the delay between real movement and its display in virtual space can reach 200 milliseconds. It consists of receiving and processing data from the video analysis system, transferring it to the graphics station, rendering, and displaying the final image on the screen.

In the future, the text will consider the aircraft's joint visual and dynamic simulation to illustrate the possible desynchronization and methods of their compensation.

2.2. Dynamic Simulation Task Description

Let us consider a particular problem. There is a specific model of a heavy aircraft (HA). All forces acting on HA and the state vector at any moment, aircraft parameters, and flight trajectory are known. It is necessary to simulate the vector of gravitational-inertial forces and angular velocity acting on the pilot on the stand.

Let us choose a physiological coordinate system associated with the aircraft: x - is directed along the central axis of the aircraft, y – along the right-wing, z – we will define it to get the right-hand-system, we put the origin at the point $C$ — aircraft center of mass.

To begin with, let us take several simplifications: the mass of the aircraft is constant (the fuel burns out evenly and slowly, we consider a reasonably short time at which the mass of the fuel can be considered constant), the center of mass is constant, there are no atmospheric phenomena, the force of gravity is constant, the Earth is flat, symmetry in the $xz$, plane, the forces of the engine act along the axis of the plane. The coordinate system associated with the Earth is considered inertial. The center of mass of the aircraft is motionless relative to HA.

Then the dynamics of the aircraft can be represented by the following system:

$$
\begin{align*}
M \ddot{y}^p &= R^e + R^{aero} + Mg, \\
\frac{d}{dt}(I\omega^p) + \omega^p \times I\omega^p &= M_R^p + M_R^{aero},
\end{align*}
$$

where $y^p$ is the position of the center of mass of the aircraft in a stationary space, $R^e$ are the forces of the engines, $R^{aero}$ are the aerodynamic forces, $g$ is the free fall acceleration, $\omega^p$ is the angular velocity of the aircraft, $M_R^e$ are the moments of the engines, $M_R^{aero}$ are the aerodynamic moments. As
with any rigid body, the HA motion could be represented as the motion of the center of mass and around the center of mass.

Let us introduce the overload for the aircraft as follows:

\[ n^C = \frac{1}{g_0} (W^C - g) = \frac{1}{g_0 M} (R^e + R^{aero}). \]

The software implementation of the aircraft model is a "black box," there is access to the model output in the form of overload \( n^C(t) \), angular velocity \( \omega^C(t) \) and transformation \( T_x^P(t) \) (Fig. 1), which sets the position pilot seats in a virtual environment.

It is important to note that an attempt to simulate directly \( n^C(t) \) on a mobile stand in parallel with visualization of the situation behind the cockpit from the pilot's seat will lead to a mismatch of effects. Indeed, let us consider the movement of the center of mass of the pilot's body, fixed on his seat by a particular spring system. During the flight, the pilot's body changes its position \( N_p \).

However, these changes are small enough, so we will perform calculations at the design point \( N \), which coincides with the pilot's center of mass at the initial moment.

\[ m \ddot{x}_p + \epsilon \dot{x}_p + k x_p = F_p = m(g - W^N). \]

Since the pilot is not in the center of mass of the aircraft, additional accelerations \( W^\alpha \) occur:

\[ W^N = -W^C + W^\alpha, \]

\[ F_p = mg + mW^N = m(g + W^N) = mg_0 \frac{g + W^N}{g_0} = mg_0 n^p, \]

where \( F_p \) is the vector of gravito-inertial forces.

\[ n^p = -n^C + \frac{1}{g_0} W^\alpha, \]  \hspace{1cm} (2)

where \( n^p \) is the pilot's overload vector.

Ultimately, we get that the pilot during the flight experiences the same overloads as the aircraft, with an accuracy of the sign and inertial forces arising due to its rotation relative to the center of mass. Thus, for correct simulation, it is required to recalculate the overloads, taking into account the rotation of HA.

Let us present a diagram of the relationship between various types of imitation and other blocks of the mixed reality system. (Fig. 2).

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**Figure 1.** Coordinate transformations
2.3. Motion Stand Description

Let us assume that the dynamics of a motion stand are known, which is presented in the form of a manipulator’s arm with a chair at the end (Fig. 2). It is important to note that we do not know precisely the parameters of the stand (both kinematic and dynamic). Let us present the equations of dynamics for a stand based on an industrial robotic manipulator, taking into account the uncertainties:

\[
\begin{align*}
\dot{x}_a &= x_b \\
\dot{x}_b &= Q^N(x_a, x_b, \mu_1 \xi_a) + Q^U(x_a, x_b, \mu_1 \xi_a) + (G^N(x_a, \mu_2 \xi_a) + G^U(x_a, \mu_2 \xi_a))u \\
\dot{\mu}_a &= \xi_b \\
\dot{\xi}_b &= Q^N(x_a, x_b, \xi_a, \xi_b) + Q^U(x_a, x_b, \xi_a, \xi_b) + (G^N(x_a, \xi_a, \xi_b) + G^U(x_a, \xi_a, \xi_b))u
\end{align*}
\]

Where \(x_a \in \mathbb{R}^3\), \(\xi_a \in \mathbb{R}^3\), \(x_b \in \mathbb{R}^3\), \(\xi_b \in \mathbb{R}^3\) are angular coordinates and speeds for three degrees of freedom of the robotic arm and three degrees of freedom of the cabin, respectively, \(Q^N\) and \(G^N\) are known matrices, \(Q^U(\tau_d, md)\) and \(G^U(\tau_d, md)\) is uncertainty associated with inaccurate knowledge of the mass-dimensional characteristics of the system (we denote the unknown parameters \(md\) and \(\tau_d\) for mass and overall dimensions, respectively).

It is challenging to solve the problems of dynamic simulation for such a system. However, using small parameters in front of the derivatives and on the right-hand sides, it is possible to significantly simplify the synthesis and find control with an error \(O(\mu)\). The first-order accuracy concerning small parameters is achieved. In the article [3] and the monograph [4] A. Vasil'eva described a general approach to solving problems with singular perturbation based on the method of boundary functions and Tikhonov’s theorem. We will solve the problem of finding the optimal control for simulating motion for a simplified system, that is, a system in which \(\mu = 0\), and write down the resulting trajectory. Then we apply the found control to the original system and solve the stabilization problem around the trajectory obtained for the degenerate system to minimize the error. At the same time, the angular motions of the cockpit will be considered under the assumption that the linear motions are quasi-stationary. Thus, the linear and angular movements of the stand can be considered separately if the parameters \(\mu_i \ll 1\).

2.4. Synchronization Problem

Suppose that one of (or a combination) of motion cueing algorithms is implemented, i.e., the control \(u(t)\) is known. Let there be an estimate of the state vector \((\hat{x}_a, \hat{x}_b, \hat{\xi}_a, \hat{\xi}_b)\), obtained using an
external tracking system (optical, inertial, or hybrid) at time $t$. We can obtain $\tilde{T}_x(t - \Delta t)$ as the estimated conversions between a fixed room coordinate system and the pilot's seat in the simulator.

Let there also be some unknown dynamics of the human head relative to the chair. Consider a particular case when a person is fastened with seat belts, and the head can only make rotational movements. The resulting movement in the moving coordinate system will be denoted as $T_z(t)$. Suppose that the tracking system allows at time $t$ to estimate the head rotation relative to the chair $\tilde{T}_z(t - \Delta t)$.

The problem of synchronizing visual and dynamic simulation is the search for such a transformation matrix $T_z^p(t)$ of the coordinate system associated with the aircraft seat to the coordinate system of the virtual camera (according to the representation in Fig. 2) so that for each moment of time $t$ the following is performed:

$$J(T) = \sum_{i=1}^{3} \left[ |\omega_i^{phead}(t) - \omega_i^{head}(t)| - \epsilon \right]_+ \rightarrow \min$$

(4)

Here $\omega_i^{phead}(t)$ is the angular velocity of the human head in virtual space, $\omega_i^{head}(t)$ is the angular velocity of the human head in reality, $\epsilon$ is the sensitivity threshold of the semicircular canals, $[.]_+$ is the operator:

$$[x]_+ = \begin{cases} x, & \text{if } x \geq 0 \\ 0, & \text{if } x < 0 \end{cases}$$

(5)

The final transformation that solves the visualization problem will be represented as:

$$T(t) = (T_z^p(t)T_z^P(t))^{-1}T_{obj}(t)$$

Where $T_{obj}(t)$ is the known movement of the visualized object, $T_z^P(t)$ is the movement of the aircraft specified from the model, $T_z^P(t)$ is the movement of the virtual camera. It is directly calculated from the movement of the real motion stand $T_x(t)$ and the movement of a pilot relative to the chair $T_z(t)$ by solving the estimation problem according to the measurements of inertial and optical sensors.

The solution to the synchronization problem is based on the solution of several subtasks, which are discussed in more detail in several articles:

- Tracking angular movements of a pilot and a motion stand using a hybrid approach and restrictions on the dynamics of the system [5];
- Identification of unknown geometric and dynamic parameters of the motion stand $(Q_U(td, md)$ and $G_U(td, md))$ in order to reduce modeling errors [6];
- Forecast of the angular motion of the stand taking into account its dynamics and tracking delay time [7];
- Increase the rendering sampling rate to shorten the motion prediction interval using foveated rendering solution [8].

It is important to note that due to (3), predicting the stand's angular motions can be solved independently of the linear ones.

3. Modelling Results

The modeling was performed at the Lomonosov Moscow State University Panoramic Virtual Reality System. Due to the limited motion capabilities of the existing platform, a separate movement along the pitch angle was carried out. The sequence of angular maneuvers of the aircraft was taken as the movement (Fig. 3). The sampling rate was chosen to be 50 Hz ($50 \text{ Hz} = 1 \text{ s}$). Several experiments have been carried out comparing the standard linear prediction (the angular velocity is assumed to be constant) with the complex synchronization between visual and motion cueing given above (Fig. 4).
Figure 3: Aircraft angular motion produced by simulator

Figure 4: Synchronization error sorted by introduced delay $t_p$ (seconds)
4. Conclusions

Performed experiments demonstrate that an increase in the delay time $t_p$ produces an insignificant decrease in the accuracy of complex synchronization. In contrast, the error in the linear prediction increased in proportion to the increase in the delay time.

Advanced synchronization methods significantly improve training systems and virtual reality systems, reducing motion sickness. The presented results could be easily transferred to other types of simulated transport and configurations of motion platforms. Synchronization becomes a more difficult task in conditions of active movement of the user in space since it becomes more challenging to build a good forecast of movement.

Further development of the problem is seen as using differential neural networks [9] to reduce uncertainties in the system and sliding mode control [10] to ensure the robustness of a moving platform.

Acknowledgments
The article was prepared within the interdisciplinary scientific and educational school of Lomonosov Moscow State University "Brain, Cognitive Systems, Artificial Intelligence"

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