On the Characterization of a Speed-boat Motion for Real-time Motion Cueing

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Keywords: Real-time Simulation, Virtual Reality, Speed-boat, Motion Characterization, Motion Platform, Inertial Cues.

Abstract: Motion platforms are not uncommon for car and flight VR simulators. However, the same is not true about watercraft. This paper presents an experimental characterization of a speed-boat in order to understand the nature and magnitude of a typical small watercraft motion. Unlike other studies, this work focuses on real-time simulation instead of on boat design issues. The purpose of the study is to guide the future process of designing and parameterizing a suitable motion platform for a VR application. The characterization is performed by placing two accelerometers, two gyroscopes, one GPS logger, one digital compass, and one digital anemometer on a speed-boat at several ranges of motion and maneuvering. We analyze tilt, speed, wind, steering, angular speed, acceleration and angular acceleration at both frequency and time domains. Characterization results show that at least a 3-DoF heave-pitch-roll motion platform should be used.

1 INTRODUCTION

Motion platforms have been used since the beginning of the VR era. However, their use has been concentrated on flight and car simulators, and there are, to our knowledge, much fewer approaches to apply this technology to watercraft. In an effort to make this technology usable and affordable for the simulation of small boats, we present an experimental characterization of a speed-boat. The information obtained from this work will help us in the design of the physics model of our simulator, and in the design and construction of a suitable motion platform. Unfortunately, we have not found any related work that tries to characterize the 6 degrees of freedom (DoF) of a watercraft motion with the purpose to reproduce it with a motion platform in a real-time simulator. Nonetheless, similar studies have been previously performed on other types of vehicles, mainly land and air vehicles. Although the behaviour of a marine vehicle is substantially different to those ones, the procedure could be extrapolated. One of the best works that deals with the characterization of a vehicle for real-time simulation is the one performed by G. Reymond and A. Kemeny (Reymond and Kemeny, 2000). Throughout this paper, we will perform a similar analysis but on a speed-boat.

The rest of the paper is organized as follows. In section 2 we describe the sensors. Section 3 deals with the analysis itself. Finally, section 4 summarizes the conclusions that we can draw from our analysis.

2 CHARACTERIZATION SET-UP

In order to record the necessary data, we used a laptop connected to a number of sensors placed on the boat. In particular, we used two 3-axis accelerometers, two 3-axis gyroscopes, one GPS logger, one digital compass, one anemometer, a microphone and a camera.

The accelerometers and gyroscopes were Nintendo Wiimotes (with Motion Plus) used to obtain linear accelerations and angular velocities respectively. We used two of these devices, as one was placed at the Center of Mass (CoM), and the other one was placed on the rudder in order to track the steering. The GPS logger selected was the Holux M-241 (Holux, 2009). To ameliorate the effects of its large vertical error, we used the GPS only to track motion and speed over the XY plane. As its 1 Hz update frequency is also quite poor; we can mix information from the accelerometers and from the GPS to obtain a better estimation of speed. The

Casas S., Coma I., Riera J. and Fernández M..
On the Characterization of a Speed-boat Motion for Real-time Motion Cueing.
DOI: 10.5220/0004272302750278
In *Proceedings of the International Conference on Computer Graphics Theory and Applications and International Conference on Information Visualization Theory and Applications* (GRAPP-2013), pages 275-278
ISBN: 978-989-8565-46-4

digital compass was an OS3000 (Ocean, 2007). The anemometer was a Kestrel 4000 (Nielsen, 2009). We also used a simple digital microphone and a webcam in order to have the test recorded. The devices were arranged as explained in Figure 1. As the data acquired from the sensors was time-stamped, it was fairly easy to synchronize it.

Figure 1: Sensor placement.

3 ANALYSIS AND RESULTS

In this analysis, we tested a *Duarry Brio 620* speed-boat propelled by a *Suzuki DF 140* Four Stroke 140 hp engine. It has a weight of 911 kg and a size of 6.20 x 2.20 x 1.43 meters (length x width x height). This can be considered an average speed-boat, and this is the reason why we chose it. The test consisted on 2030 seconds of boat manoeuvring near the Port of Barcelona, which can be divided into certain time zones (see Table 1).

All the calculations and analysis of the collected data were performed using MATLAB 2009.

3.1 Global Analysis (Ranges)

Virtual vehicles are not critically affected by peak values of speed, acceleration, or any other physical magnitude. Nevertheless, as we intend to reproduce the boat's motion with a real motion platform with real physical limits, measured peak values are important in order to know whether or not our motion platform will be able to withstand such limits. Peak values need to be taken with caution for they are usually the consequence of a precise and unique moment, but they reveal some information. Table 2 shows the peak values observed during our experiments. Our frame of reference follows the *X-right, Y-forward, Z-up* convention.

For instance, from this data, we can see that the boat leans to positive pitch. This is a direct result of the design and engineering of the speed-boat. Unlike the pitch angle, roll angle is symmetrical around the Y axis. Besides, roll maximum value is a little lower than pitch (positive) peak value. Yaw angle is, not surprisingly, unbounded.

Table 1: Test chronology.

Range(secs)	Description
0-260	Set-up and testing (discarded)
260-440	Docked
440-550	Manoeuvres inside port
550-800	Slow navigation near port
800-980	Progressive acceleration
980-1320	Full-speed navigation
1320-1355	Braking and then stopped
1355-1553	Open sea moderate navigation
1553-1613	Navigation, braking and reverse motion
1613-1770	A variety of manoeuvres
1770-1885	Full speed turning
1930-2030	Stopped at sea

Forward acceleration peaks around 0.4 Gs and -0.8 Gs. Negative accelerations are related to fluid braking. Water is a very tough fluid to move through, and it is able to stop the boat rapidly. Positive accelerations should be related with engine propelling. However, a further analysis will reveal that both are a result of water hits instead of the engine. Lateral acceleration peaks around ±0.5 G, which is not much. It is symmetric as expected because it is produced by turns and water hits. Vertical acceleration ranges from -2 Gs to 1 G, which is quite a larger range. This shows that one of the most noticeable effects of being on a speed-boat is water hitting when jumping from wave to wave. Both positive and negative peaks are caused by water waves hitting the boat. These accelerations are very short but also very sharp, and thus, noticeable.

Angular velocities are also consistent with the boat's motion for they are lower around the Z axis (yaw) than around the other two. Indeed, a boat suffers high-frequency rotations around pitch and roll axes, but although it is able to turn (yaw) quickly, it cannot reach the angular velocities of the other two axes. Angular velocity around Y axis is a little greater (the difference is in fact greater because of outliers) than around X axis. This is also consistent with the boat design, because the boat is longer than wider. Travel speed ranges from a few knots when travelling backwards to more than 25 knots on forward advance. The boat is not designed to travel backwards because it tends to sink, so maximum backward speed is very limited.

Apparent wind speed ranges from 0 to more than 30 knots. It is similar to forward speed, as expected.

Table 2: Observed ranges.

Magnitude	Min	Max	Units
Yaw	0.0	359.99	°
Pitch	-5.3	+21.73	°
Roll	-19.18	+19.86	°
Forward acceleration	-0.83	+0.42	Gs
Lateral acceleration	-0.45	+0.61	Gs
Vertical acceleration	-2.11	+1.15	Gs
Angular speed X	-118.1	+132.9	°/sec
Angular speed Y	-144.8	+110.9	°/sec
Angular speed Z	-42.6	+58.85	°/sec
Forward speed	-5.64	26.71	knots
Apparent wind speed	0.32	32.46	knots

3.2 Time Domain Analysis

A time-domain analysis of the data reveals some interesting facts. The first one is that pitch and roll show a different behaviour. They both depend on swell and speed, but on a different fashion. While pitch tends to increase with speed (because the engine generates an off-axis force that creates a lifting torque) and gets affected by waves, roll seems to have an opposite behaviour, because roll is much higher when the boat is stopped and at swell's mercy. To corroborate this, we computed the Pearson correlation between forward speed and pitch and the result was 0.826. The roll-speed correlation was -0.218 that reveals some degree of inverse correlation.

The time-domain analysis of the linear acceleration reveals that, in spite of testing a speed-boat with a 140 hp engine, no trace of a sustained Y acceleration caused by the engine is found. We can see that in Figure 2 (where we show time vs. acceleration). Although a speed-boat could reach 30-40 knots, it takes several seconds to reach that speed, and the average Y acceleration is even smaller than that of a utility car. If we compute the average forward acceleration from 890 to 910 seconds (maximum acceleration zone) the result is less than 0.2 Gs. The absence of high sustained accelerations on the Y axis is good for the design of a motion platform, because sustained accelerations produce long displacements. X and Z accelerations show a similar behaviour, although the Z acceleration is larger and sometimes sharper.

The analysis of the angular acceleration shows that all three components present a sinusoidal shape, with some very sharp peaks, that are the result of water hits, but, again, no trace of sustained angular acceleration is found. This means that if we want a motion platform to reproduce X and Y turns, we need powerful engines to reproduce sharp changes, but the absence of sustained acceleration assures us to be within the limits. Regarding the Z axis, there is some sustained angular speed that indicates that to simulate that kind of motion we need a motion platform with as large excursion as possible. In any case, as the angular accelerations are not sustained (not even on the Z axis), the motion platform could trick that with an appropriate washout algorithm (Reid and Nahon, 1985). For the sake of brevity we cannot show graphs of all the tested magnitudes.

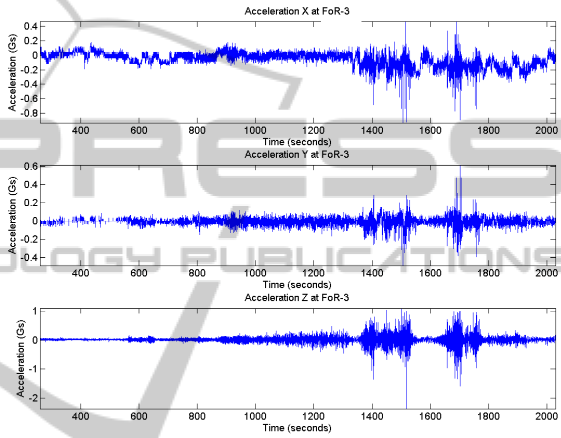

Figure 2: Linear acceleration.

3.3 Frequency Domain Analysis

Although on time domain we can see the behaviour on different situations, the analysis of the spectral distribution of the measures is necessary to asses which motion cues will be compliant with the future motion platform rendering performances. The best way to analyse this is to calculate the cut-off peak-to-peak maximum displacements. The peak-to-peak amplitude of the displacement signals were computed by applying a second-order high-pass filter of cut-off frequency f_c, to the accelerations, and then double-integrating into positions, exactly like Reymond and Kemeny did (Reymond and Kemeny, 2000). The resulting curves of peak-to-peak amplitudes for different cut-off frequencies are shown in Figure 3.

As we can see, eliminating all frequencies lower than 3 Hz the excursion needed for the motion platform is (22.9, 13.7, 52.7) cm (X, Y, Z) which is feasible. If we eliminate all frequencies lower than 5 Hz the excursion needs to be (12.3, 7.4, 28) cm, which could be easier to achieve. As we decrease the cut-off frequency under the 3 Hz limit, the limits raise exponentially. As we can see, Z excursion needs to be higher than X and Y. This is a consequence of the absence of sustained X and Y accelerations, and also a consequence of sea tide, which lifts the boat whenever a wave passes under it, creating a short but more sustained Z motion.

The same can be done with peak-to-peak angles. In this case, pitch (X) and roll (Y) angles do not need to be larger than (approximately) 20° and the yaw angle (Z) is unbounded. This means that pitch and roll movements could be simulated directly without filtering provided that the motion platform withstands those limits (Nahon, 1990). Z turns have to be filtered because yaw motion is not constrained but the motion platform usually is. This is consistent with the measurements of Section 3 and with the nature of the motion. Following with the analysis, with a 3 Hz cut-off frequency, the excursion needed is (12.18, 10.9, 9.4)° (X, Y, Z). With a 5 Hz limit, the excursion needs to be (10.8, 9.7, 6.6)°, and with a 10 Hz limit, we need (8.52, 8.53, 3.87)°. Here, an increase in the cut-off frequency does not change as much as it did with the translational limits (with the exception of yaw) and the 3 Hz limit is totally feasible without losing much information.

4 CONCLUSIONS

Some conclusions can be drawn from our study. On the qualitative side, we can affirm that the four major cues when sailing a speed-boat are pitch, wind speed, roll and heave. Pitch is the major cue because it is directly linked to the throttle and, at full speed, considerable pitch angles are reached. Wind speed is quite important because, unlike in a car, no windshield protects you from the air, and the feeling of the wind is fairly intense. Roll is less significant at high speeds but when the boat is turning or stopped, it is also quite noticeable. And heave is also important when the boat hits a wave. These qualitative conclusions are consistent with our data.

On the quantitative side, the most important conclusion is that sustained accelerations (low frequencies) are rather small and that water, and not the propeller, is the main cause of inertial cues. This is a significant result because it means that it is more important to be able to produce fast but sharp movements than long accelerations. Therefore, the motion platform excursions do not have to be very long. However, the engines should be strong enough to move the platform as quickly as possible. Another conclusion that can be extracted is that motion along Z axis is the most important of the linear motions. As aforementioned, pitch and roll rotations also reveal very important, because they change sharply and they define the behaviour of the boat. On the contrary, yaw rotations tend to be less important compared to the former. Thus, if we were to choose a motion platform design, we would build a 3-DoF pitch-roll-heave motion platform. In our opinion, this is the minimum necessary to reproduce the major inertial cues of the boat.

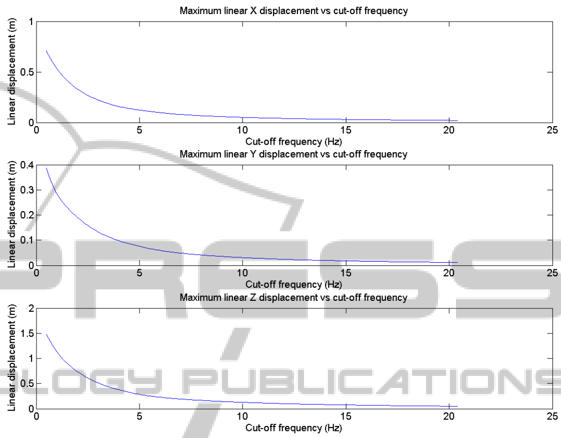

Figure 3: Cut-off peak-to-peak maximum linear displacements.

Future work includes, of course, building a suitable motion platform and a real-time simulator to use it. Some of the future work is already published in (Casas et al., 2012).

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