Int. J. Simulation and Process Modelling, Vol.
This is the authors' preprint version.
See editor's version at https://doi.org/10.1504/IJSPM.2011.048009

New developments in simulation-based harbour crane training

Ignacio García-Fernández, Marta Pla-Castells,
Miguel A. Gamón and Rafael J. Martínez-Durá*

IRTIC, Universitat de Valencia,
C/Catedrático José Beltrán, 2, 46980 – Paterna (Valencia), Spain
E-mail: ignacio.garcia@uv.es
E-mail: marta.pla@uv.es
E-mail: miguel.a.gamon@uv.es
E-mail: rafael.martinez@uv.es
*Corresponding author

Abstract: This paper presents the efforts that have been made during the development of a set of harbour training simulators to improve their quality. The paper focuses on two main research lines: the improvement of complex physical systems involved in the simulation and the analysis of hardware architecture solutions. Cable-based hoist systems and bulk materials are systems present in different harbour equipment and are usually simulated with poor quality due to their complexity. In this paper physics-based models for the interactive simulation of these systems are proposed and applied to real cases. Also, different hardware simulator architectures are analysed and different approaches are proposed to the problem of choosing the devices for a simulator.

Keywords: training simulator; virtual reality; harbour training; harbour simulation; immersive systems; Stewart platform; tracking device; crane simulator; driving simulator; granular system modelling and simulation; cable modelling and simulation.

Reference to this paper should be made as follows: García-Fernández, I., Pla-Castells, M., Gamón, M.A. and Martínez-Durá, R.J. (2011) 'New developments in simulation-based harbour crane training', *Int. J. Simulation and Process Modelling*, Vol.

Biographical notes: Ignacio García-Fernández received his BSc in Mathematics by Univ. de Valencia in 2000, his MSc in Computer Science in 2003, and his PhD by Univ. de Valencia in 2009. His main research interest are physically-based modelling and simulation for virtual environments.

Marta Pla-Castells received her BSc in Mathematics by Univ. de Valencia in 2000, her MSc in Computer Science in 2004, and her PhD by Univ. de Valencia in 2009. His main research interest are physically-based simulation and computer graphics for virtual reality applications.

Miguel A. Gamón received his grade on Computer Engineering by Univ. de Valencia in 2002 and his MSc in Computer Science in 2005. His main research interest are computer graphics and Human-Machine interfaces.

Rafael J. Martínez-Durá received his BSc in Informatics by Univ. Politécnica de Valencia in 1991, and his PhD by Univ. de Valencia in 1997. His main research interest are visualisation systems for virtual reality applications and sensorisation systems. He is the Director of the Modelling and Simulation Laboratory.

1 Introduction

In the last decades, interactive simulation based on virtual reality techniques has become a powerful tool for training purposes, especially in activities that involve high risks and costs, as it is the manipulation of heavy harbour equipment (Stone, 2001; Kim, 2005). The many benefits that can be obtained from the use of a simulator in training tasks have motivated an increase of the use of such systems in the marine and port environment (Serón et al., 1999; Huang, 2003; Daqaq and Nayfeh, 2004; Rouvinen, 2005; Korkealaakso et al., 2007; Bruzzone et al., 2008; Li and Wang, 2009).

The use of a simulator forces the trainee to practise the theoretical concepts that have been taught and shows the consequence of the actions in a very immediate and visual manner (Farmer, 1999). The simulator also provides the instructor with a controlled environment where a large amount of data can be recorded and analysed to evaluate the trainee's evolution.

From the risk prevention point of view, it avoids the danger caused by inexperienced user manipulating the real machine in the real working environment. Furthermore, the simulator reduces the cost associated to training; it reduces machine breakdown due to misuse by inexperienced operators and avoids the use of real machines just for training purposes.

In addition, the simulator makes it possible to work in any desired conditions. Arbitrary weather conditions can be reproduced and, thus, training can be made for climate conditions of a given harbour thousands of kilometres away. Thanks to the simulator it is also possible to reproduce emergency situations, new operation strategies, unusual work load and many other scenarios that cannot be set up easily in the real terminal.

Many harbours around the world are currently profiting from the benefits of simulation technologies for training crane operators. Several companies and universities have presented different systems for crane operator training during the last decade for different types of cranes (Jones, 2002; Drilling Systems, 2011; Globalsim, 2011; MPRI Ship Analytics, 2011; LAMCE, 2011; ARI, 2011; ABB, 2011; Total Soft Bank, 2011; LSyM, 2011).

In this paper we address two of the issues that have to be considered during the development of a simulator: the modelling of the physical systems that appear in the virtual environment and the adaption of the hardware devices to fit different training needs. The paper is structured as follows: In what remains of Section 1 the training system and its main elements are described. Section 2 provides an overview of the state of the technology. In Section 3 the models of granular systems and cable and pulley systems are presented. Section 4 explains the solution that is proposed to obtain a flexible hardware simulation system. Finally, Section 5 gives concluding remarks and an overview of future work.

1.1 Training system description

The training system that motivates this research is a simulator based on Virtual Reality techniques aiming at harbour machinery operation. The system is comprised of three main elements:

- the instructional design
- the user management and evaluation system
- the simulation system.

The goal of the instructional design is to provide the simulator with a guide for the training process and to optimise the results obtained with the system. The instructional design consists of a series of exercises and training routes associated to the goals of the training process. In order to save a record of the results of every trainee, for further analysis or report generation, a training system usually includes a user management system, consisting of a database to store all relevant information. Together with this database, a series of evaluation algorithms make it possible to evaluate the trainee, compare the performance of different users and analyse their evolution.

1.1.1 Simulation system

Together with the instructional and database modules, the training system includes a simulator, which is the module that is actually used during training activities. A simulator is a complex system in itself and it is composed, in turn, by several subsystems:

- the image generation subsystem, which provides a graphical representation of the environment
- a physically-based model of the machine and the environment
- hardware devices including the projection system, the cabin and a 6-Degree of Freedom (DOF) mobile platform
- an instructor's console which provides the instructor with full control over the training system.

All of them are closely coupled in such a way that the actions over any simulator control or input device are received by the dynamic model, producing a reaction that is observed immediately by the simulator's operator, thus, leading to a high degree of interactivity.

The state of the simulated environment is reproduced by means of the image generation subsystem, a 3D graphics application which stores a scene graph of the virtual world. This application is implemented by means of the OpenGL Performer and Open Scene Graph programming libraries. Also, it uses several state-of-the art techniques to reproduce different weather conditions, the aspect of the sky at different day times and high quality rendering of water in real time (Tessendorf, 1999), as seen in Figure 1.

The dynamic models are a combination of multi-body models, implemented by means of the ODE programming library (Smith, 2004) and a set of mathematical models of other complex systems, which have been developed and implemented by the research group.

The cabin holds the different Input/Output devices and is fixed to a 6-DOF mobile platform. The platform is controlled using the outputs of the dynamic to simulate the accelerations experimented in the real machinery (Reid and Nahon, 1985, 1986) in order to provide a higher degree of *presence*, which is defined as *the feeling of being there* in a virtual environment.

Based on the described architecture, the system is able to reproduce the behaviour and working environment for five harbour machines: quay-side gantry crane, rubber-tired gantry crane, mobile crane, reach-stacker crane, and ro-ro tractor.

Figure 1 The virtual environment includes state-of-the-art techniques for real-time rendering. In the picture, an image of the high quality ocean model, which includes both rendering and simulation of water (see online version for colours)

1.2 Contribution of this work

This paper presents the efforts that have been devoted to increase the quality and realism of harbour crane simulation by means of two main contributions. On the one hand, the improvement of some complex physical systems involved in the virtual environment, using novel modelling methodologies. These systems are bulk materials, handled by mobile cranes, and cable-based hoist systems, present in many harbour equipment. On the other hand, a set of hardware solutions developed to obtain a flexible simulation system that can be useful for different requirements and training needs.

2 Related work

The subject of simulation for training has motivated many research and commercial projects during the last decades. A number of works have contributed to the research and development of several aspects of this field, proposing different system architectures, specialised dynamic models of the cranes, collision detection algorithms or projection system configurations.

One of the aspects that are studied in this work is the physically-based modelling of the cranes and of different systems of the environment. From this point of view, probably the types of cranes considered most often are the quayside gantry cranes and the yard gantry cranes which, for the latter can be either rail-mounted or rubber-mounted. These cranes, used for lifting containers, can be considered as an elevated beam structure along which a carriage can move. Suspended from this carriage a steel cable hoist system holds the spreader, which is the device that takes the container from the yard, from a truck or from the vessel.

For these cranes, the dynamic models are usually divided into three rigid bodies: the gantry, the trolley and the payload (Rouvinen, 2005; Korkealaakso et al., 2007). In a standard model, the gantry has one DOF parallel to the dock edge and the trolley has one DOF perpendicular to the previous one. In some cases the structural flexibility of the gantry is also considered, thus, adding an additional DOF in the vertical direction.

The spreader is a body that hangs from a series of steel cables connected to it by means of pulleys. These body is usually modelled as a free body, with 6-DOF, under the action of springs to model the elevation cables (Bruzzone et al., 2008). Some authors have proposed more sophisticated models of spreader, including the pieces of metal that guide it in the final approximation to the container. These guides are of great importance to allow a fast and precise positioning of the spreader on the load (Rouvinen, 2005).

Beyond these two types of cranes, the mathematical models that describe the physics involved are usually more sophisticated. Some harbour equipment are different types of vehicles. Examples of such machinery are truck heads and trailers, ro-ro tractors or reach-stacker cranes. The mathematical modelling of their physical properties has to reflect the different bodies and mechanical joints present in the machine, as well as the interaction of the wheels with the ground (Bergamasco et al., 2005).

Boom cranes, such as harbour mobile cranes, ship-mounted cranes and offshore cranes, are articulated systems composed of several bodies connected by means of rotational joints (Abdel-Rahman et al., 2003; Daqaq and Nayfeh, 2004; Li and Wang, 2009). In addition, these systems often use cables not only to hoist the load but also to hold and move the structure of the crane itself. This has been reported as one of the most challenging elements of this class of cranes (Cooper, 2003) when real-time, interactive simulation is the goal. Moreover, these kinds of cranes have an additional interest from the modelling point of view: they are often used for handling bulk materials which, in general, are very complex physical systems. This issue, however, has been little investigated so far.

Some more general aspects related to physically-based modelling, which affect any simulator regardless of the type of crane considered, are those related to collision detection or numerical integration of the equations of motion (Rouvinen, 2005; Korkealaakso et al., 2007). These aspects, however, are outside the scope of this work, which focuses on the modelling of some particular physical systems.

The second aspect to be studied of study in this investigation is the architecture and configuration of the hardware devices that compose the training simulator. The main goals of these devices are two: providing the user with an immersive virtual reality environment and obtaining the user's actions to be used as inputs in the simulator.

When addressing the implementation of the visualisation system, the possible choices are based on the different approaches to visual immersion (Wei et al., 2008). A multi-screen system, possibly including stereoscopic vision, is a common selection, although a stereoscopic system with one screen is possible, according to the needs of every particular application type. For instance, in a gantry crane it is necessary to evaluate the container distance from the ship hull, thus, the feel of depth provided by stereoscopic imaging can be of help. In the case of the simulation of a vehicle, such as the reach-stacker crane or the ro-ro tractor, a peripheral vision is vital and a configuration with several screens that cover a wide field of view is necessary (Huang, 2003; Korkealaakso et al., 2007).

A similar discussion can be valid for other devices such as the crane control panel, tracking devices, vibration generators or motion platforms (Martínez-Durá, 2009). However, the design and configuration of such systems are not often discussed in the literature, as they are considered an implementation issue, which depend on the particular needs of every installation of a simulator.

3 Dynamic model

In order to obtain a high quality virtual environment, a realistic simulation how machine and of its subsystems behave is of crucial importance. In our work, the focus of investigation has been on increasing the simulation quality of two systems involved in the harbour environment: bulk material and hoist cables. These two systems share the property of being complex systems, which are difficult to simulate in real-time, interactive applications. In this section we describe the modelling approach that has been followed to simulate these systems.

3.1 Granular systems simulation

The simulation of a mobile crane requires the modelling of bulk material that this kind of equipment often handles. Load and unload activities in vessels, as well as the arrangement of the goods in the harbour yard, need to be simulated realistically. Despite its importance, the interactive simulation of bulk materials has not been properly simulated in the past due to its complexity.

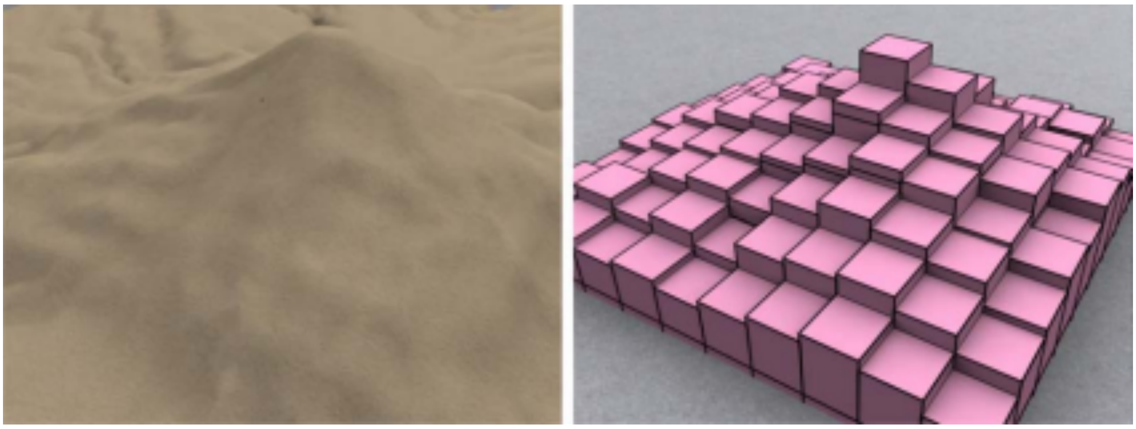
Bulk materials are granular systems, that is, they are systems formed by a large amount of interacting particles. In granular systems, the interaction between the particles causes a complex macroscopic behaviour. One of the properties of this kind of materials is that they neither behave as a solid nor as fluid or gas. This makes it difficult to include the simulation of granular systems in training simulators; while the simulation of individual particles involves a high computational cost, which is inadequate for real-time applications (Pöschel and Schwager, 2004), and building a macroscopic description of its dynamics is a complicated issue (Duran, 1999).

In order to meet both the physical realism and the computational efficiency necessary in training simulators, a model based on the cellular automata formalism has been developed for the evolution of the granular system surface (Pla-Castells et al., 2008).

3.1.1 Description of the model

The dynamic model of terrain used in the simulator is the cellular automata presented in Pla-Castells et al. (2006). In this model, geometrical representation of terrain is made by means of a height field on a regular two-dimensional grid, formed by square cells (see Figure 2). The height of the surface of the terrain or granular material over every cell (i, j) will be denoted as $h_{i,j}$. Using this discrete representation of the bulk material, a local rule computes the evolution of the height of the granular system over every cell.

Figure 2 A granular system is represented by means of a regular grid and the state of the system is described by means of a height on every cell of the grid (see online version for colours)



The local rule is based on the existence of the so-called *critical slope* of granular systems. This property states that a granular system behaves as a solid, and remains static, if the slope of its surface is smaller than certain value α_0, called critical slope. This value depends on the properties of the material. On the contrary, if the slope is higher than α_0, then a thin layer of material starts rolling down the slope, behaving as a fluid.

In the discrete model that is used in the simulator, a measure of the slope at every node is computed using the first order approximation of the gradient. This is made by comparing the height h_{ij} over adjacent cells of the grid, as it happens in the finite difference schemes for solving partial differential equations numerically (Strikwerda, 2004). If the computed slope is higher than the critical slope, then the height of the grid is reduced at that node and increased in the nodes placed downhill.

If the slope (or its numerical approximation) in the direction of index k is denoted as $\delta_k h_{ij}$, then this rule can be described using equations (1)–(3),

$$h_{i,j} \leftarrow h_{i,j} - c \cdot (\delta_i h_{i,j} + \delta_j h_{i,j}) \tag{1}$$

$$h_{i+1,j} \leftarrow h_{i+1,j} + c \cdot \delta_i h_{i,j} \tag{2}$$

$$h_{i,j+1} \leftarrow h_{i,j+1} + c \cdot \delta_j h_{i,j} \tag{3}$$

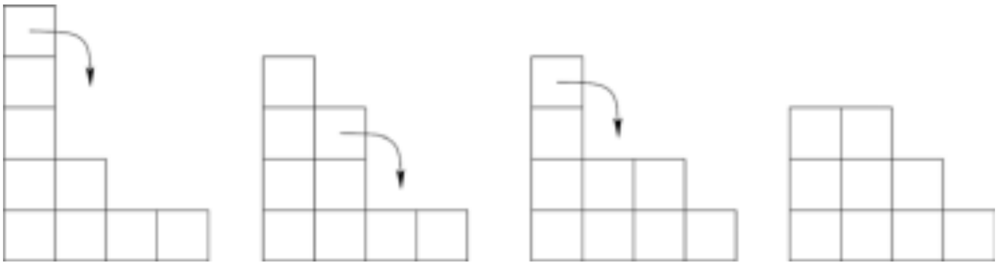
where c is a parameter that determines the speed of the avalanche and depends on the properties of the simulated material. Figure 3 shows this idea in a discrete one-dimensional example. In this example the slope is measured in terms of the difference in height between two adjacent cells. In order to simulate a pile of granular material in the virtual environment, a piece of the ground in the harbour yard can be covered by a grid and simulated with this model.

However, if the model is implemented using a straightforward scheme, checking every cell of the grid and updating it when necessary, then it has a computational cost that grows with the square of the resolution of the grid in cells per meter. Thus, as soon as the resolution of the grid is high or the covered area increases, this quickly prevents the use of the model in real time applications.

In order to overcome this problem a property of granular piles that has been observed by physicists is exploited. When the slope of a granular pile is close to the critical slope and it is perturbed (by the addition of new material or by the local displacement of particles), then it is observed that the size of the avalanches follows a $1/f$ frequency curve. This means that large avalanches are very rare, while small avalanches are very common (Bak et al., 1988).

In our implementation a list of *active cells* is updated during the simulation, which contains only the indexes of the cells that were modified in the last simulation step. If any cell was not modified, then it will not cause an avalanche in the next step and does not need to be updated. Thus, only the cells that are on the list are checked to compare their slope with the critical slope of the system saving computations. Empirical studies have shown that, using this method, the cost of the

Figure 3 A discrete one-dimensional example of the evolution model. When the slope (difference in height in this case) is higher than a certain critical slope, some of the material moves to the shorter cell



computations only grows linearly with the diameter of the pile measured in grid cells (Walter and Worsch, 2004; Pla-Castells, 2008).

3.1.2 Material-tool interaction

In addition to the simulation of the granular pile behaviour, in a training simulator it is also very important to reproduce the interaction between the crane and the bulk material. This requirement forces to build a model that is flexible enough to cope with the unexpected situations produced by the user and that is able to provide the simulator with physics-based models of the reaction of the system to such interactions.

In order to do this, first a collision detection phase is performed before every simulation step is executed, and the contacts between the objects of the scene and the granular material are computed. Then, when a collision has been detected two reaction models are executed: a reaction force is applied on the object to simulate the impact and a deformation model is applied to the granular system.

For the sake of efficiency, a simple collision detection approach has been chosen. A set of *contact points* are placed in the object to be simulated. Then, it is checked if any of them is below the surface of the granular material. Figure 4 shows the contact points for a mobile crane grab. When a collision is detected between a *contact point* and the granular material the contact depth is computed and a penalty-based force is applied to the object using a highly damped linear spring. Despite the simplicity of the approach, the results are very satisfying, as the response of the granular material is very soft and some inter-penetration is realistic.

For a good visual effect and a more realistic simulation, the deformation of the granular pile is also considered. The goal is to force the material to scape from the cells that are compressed during a collision. This behaviour is similar to that which would happen if the height of a cell is increased, as the difference in height between adjacent cells is used when computing the slope of the granular system. If, in this computation, the height of a cell is increased, then the material will tend to fall out of that cell, because the model will detect that the slope is high when compared with neighbouring cells. Thus, in order to simulate the effect of compressing a cell by a vertical force an additional height will be artificially added to that cell during the computation of the slope (Pla-Castells et al., 2004). This artificial modification of the cell's height will not be shown during the render of the scene, thus, causing a depression under the contact points. Figure 5 shows a representation of this model.

3.1.3 Material load and unload

When the concern of the model is on training, one of the aspects that has to be considered is the procedure of loading and unloading the crane grab. In addition, it is important to properly compute and record the amount of goods that is handled by the user of the simulator for evaluation purposes.

Figure 4 Representation of the contact points that have been used to simulate the interaction between the mobile crane grab and the bulk material. When any of these points is below the surface of the granular system a collision is simulated (see online version for colours)

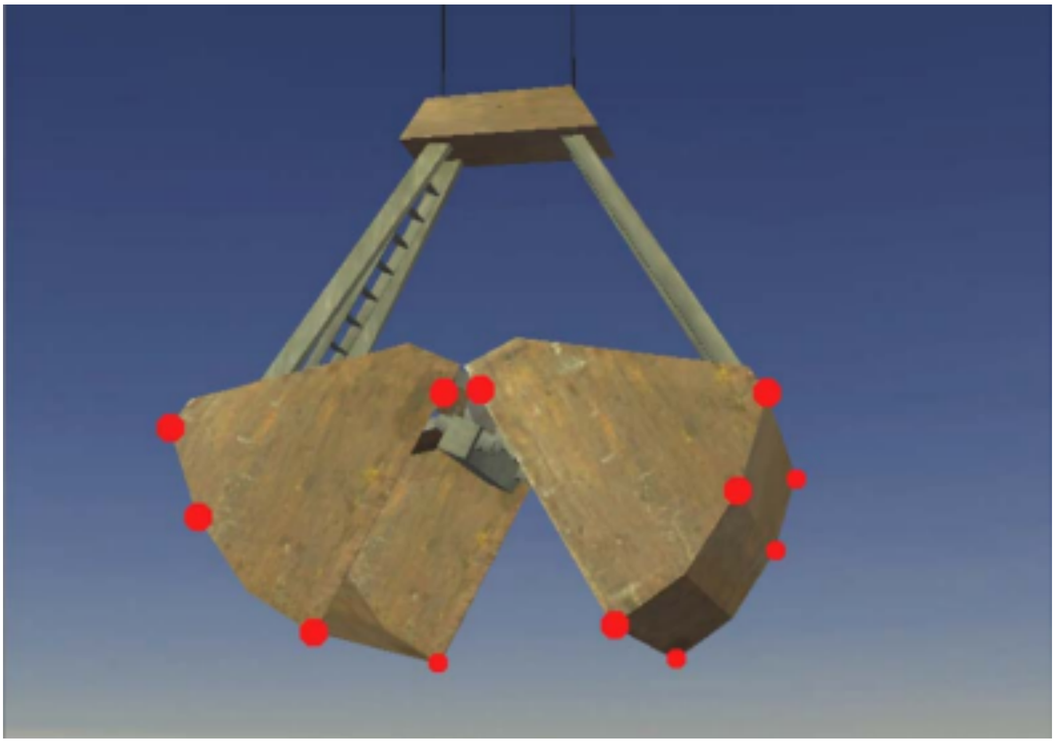
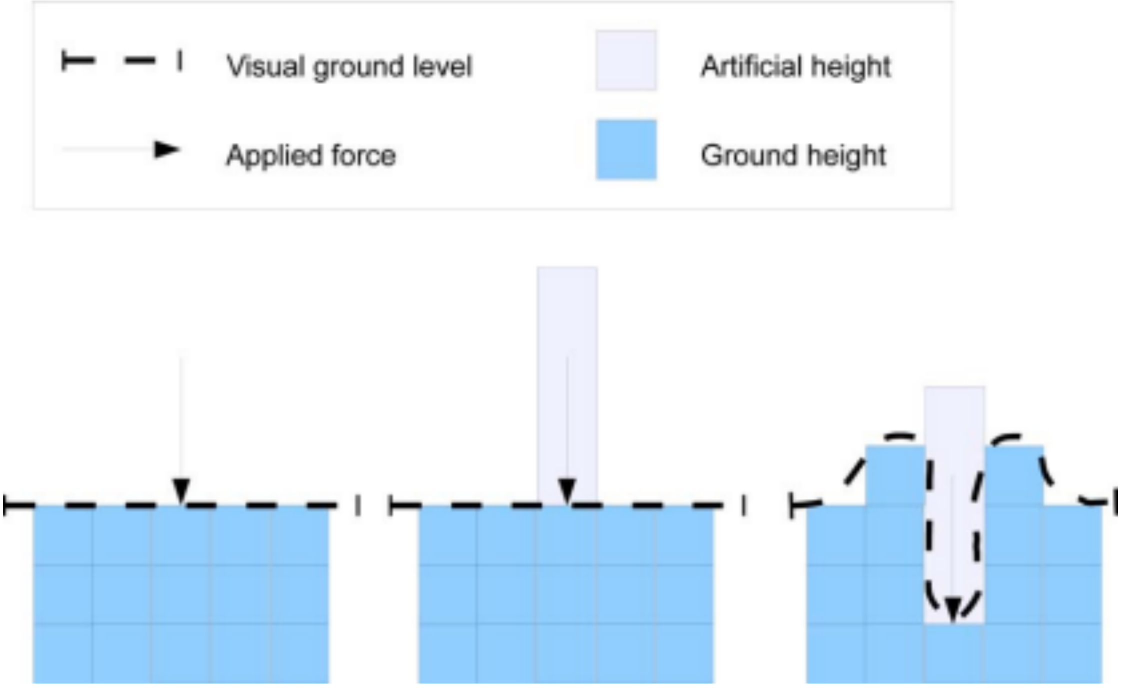


Figure 5 The deformation of soil under a pressure is considered. By means of an artificial increase of the height of the pressed cell material moves to the adjacent cells, leaving a depression (see online version for colours)



The difficulty that arises from the proposed modelling approach is that there is no explanation on how the particles of the granular system are arranged when the grab enters the material, as the model only considers the state of the granular system surface. Moreover, a model that considered big detail on the interaction of the particles with the tool would be computationally too expensive for an interactive application. For this reason our decision was to develop a qualitative model using a reduced number of variables.

The model considers three variables (see Figure 6): the width of the opening of the grab, w; the depth of the grab into de bulk material d; and the vertical grab sinkage velocity into the granular system, v. If we consider a grab of width W, the procedure to compute the amount of material, M, that has been loaded after a time interval h (corresponding to a simulation step) can be sketched as follows:

```
• $if(d > 0\ and\ v > 0)$ // the grab is sinking
      $M \leftarrow w \cdot W \cdot (h \cdot v)$
• $else\ if(d < 0)$ // the grab is not colliding
      $M \leftarrow -w \cdot W \cdot (h \cdot v_0)$
• $end\ if$
```

where v_0 is a parameter that fixes the velocity at which the material falls from the grab. After every step, the amount of material inside the grab is increased by an amount M. This amount is also used to reduce the height of the granular system when the grab stops colliding with it, and to draw a particle system falling from the grab when it is unloading bulk material. Figure 7 shows a sequence of images from a load and unload cycle.

3.1.4 *Integration in the virtual environment*

When configuring a simulation scenario, a region of the yard is defined as the *active region* and it is covered with a grid that models the bulk material. The active region is the portion of the yard from which material can be loaded and to which material can be unloaded.

Also, a set of collision points is defined for every object that needs to interact with the granular system, which typically include the crane grab and other loads that have to be handled during the simulation. If granular material has to be loaded or unloaded from a vessel, then another grid can be placed on the deck of the ship, so that material can be picked up and left. The set of models that has been described allow simulating the complete process of loading and unloading of bulk materials using a mobile crane.

3.2 *Cable and hoist simulation*

Cables and pulleys used in most elevation equipment also show a highly complex behaviour, inducing vibrations on the structure and the load. Quay-Side and Gantry cranes use a set of pulleys and cables in order to hoist the load, while in a mobile crane cables are also used to move some of its structural elements, such as the boom, as shown in Figure 8.

Due to the complexity of their dynamics, cable systems have been usually simulated as massless spring elements, discarding cable oscillation and complex pulley

Figure 6 Variables used in the model for load and unload of bulk material (see online version for colours)

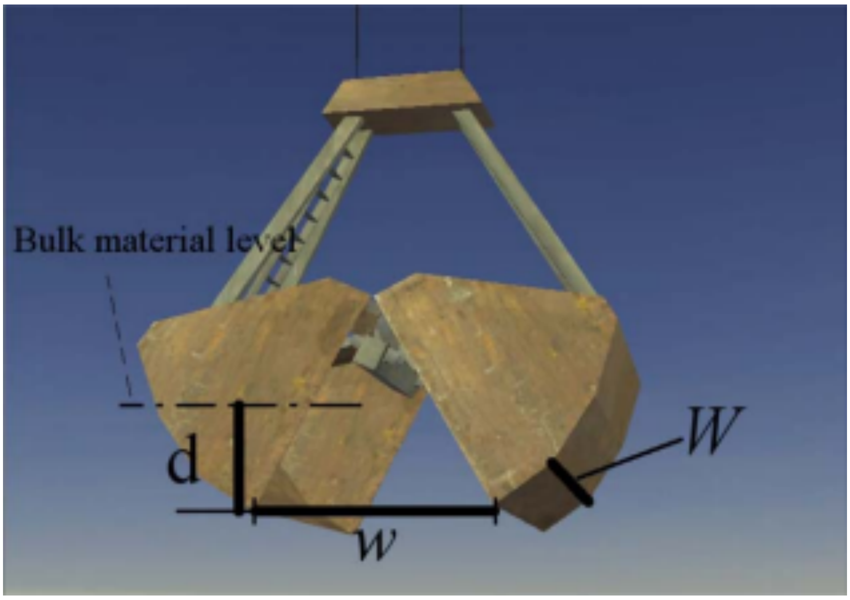
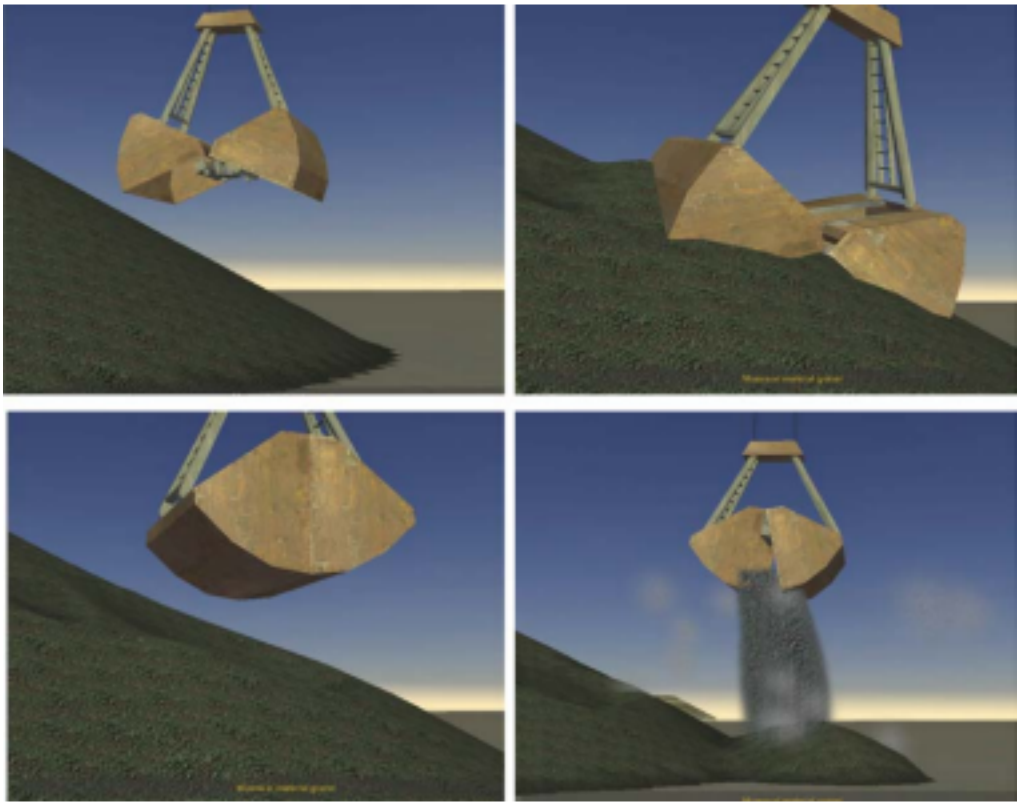


Figure 7 A sequence of the process of loading and unloading bulk material in the harbour yard (see online version for colours)



systems (Abdel-Rahman et al., 2003; Daqaq and Nayfeh, 2004; Servin and Lacoursière, 2007). However, this leads to an important loss of realism both in the visual aspect of the simulator and in the physical properties of the crane models.

For this reason, and in order to increase the quality of the simulation, a new model has been developed that considers cable oscillation and allows simulating arbitrary pulley configurations (García-Fernández et al., 2008). The modelling methodology is based on the modularisation of the cable-pulleys system. First, two entities are defined separately; a pulley and a cable segment between two pulleys. Then, for every entity a set of input and output variables are defined.

A pulley considers the tension applied by the cable segments that end on it as inputs and its rotation velocity as output. On the other hand, every cable segment considers the longitudinal velocity of the cable at its ends as input and provides its tension at its ends as output. By using this definition of pulley and cable segment,

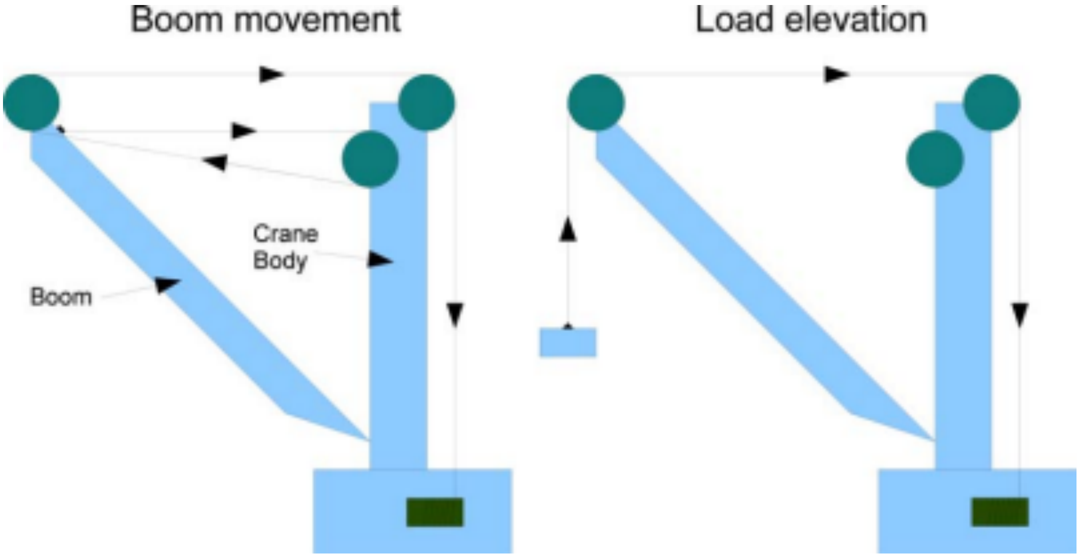
Figure 8 Cable and pulley systems are often present in harbour cranes. A mobile crane usually uses this kind of system to hoist the load and also for the movement of the boom (see online version for colours)

they can be coupled to form an arbitrary block and tackle hoist system. Figure 9 shows the hoist and boom movement system of the mobile crane that has been simulated.

One of the benefits of this approach is that any physically-based model for the dynamics of a cable segment can be used to simulate a hoist system. Moreover, two different oscillation models can be exchanged during the simulation (García-Fernández, 2009). This property is used to reduce the computational cost of the simulation and to increase its overall numerical stability as explained next.

Every cable segment is simulated using a 3-dimensional wave equation, modified to consider longitudinal velocity and the inertial forces caused when its edges are moved (due to the eventual displacement of

Figure 9 The cable and hoist model proposed makes it possible to simulate complex pulleys systems and cable oscillation. In the simulator both the boom movement system and the elevation system of the mobile crane have been modelled (see online version for colours)



pulleys). This model provides as good representation of transversal vibrations and is able to transmit the resulting forces to the pulleys and to the crane structure. This model, however, has the drawback that, beyond certain level of longitudinal tension, integrating the equations of motions becomes numerically unstable unless implicit methods are used. In this case, the numerical integration of the wave equation is suspended and the oscillation model is replaced by a massless spring model until the tension is low enough to resume the numerical integration (García-Fernández, 2009).

4 Scalable hardware configurations

A training simulator is a complex system that needs a series of hardware components to provide its users with a high degree of presence and realism. For this purpose, the Simulation System can be built with an immersive projection system and a cabin, where a seat and the input/output devices are installed. This cabin and the projection system are mounted on a 6-DOF Stewart platform, which is in charge of producing in the user inertial stimuli that simulate the accelerations experienced in the real crane.

However, depending on the needs of the harbour and the training centre, the highest range of hardware devices is not always the best option. According to our experience, different hardware configurations can be suitable for different training goals and requirements. We have grouped them into three categories. Next, we describe what kind of training they are most suitable for.

4.1 Desktop system

Among the range of centres that can be interested in using simulation for training, one of the profiles we have found is that of a training centre which already has one or several computer classrooms and would like to use these facilities without making a big investment on hardware. In this situation, the simulator has to run in standard desktop PC computers. This is also one of the main reasons for making the effort to build efficient dynamic models and algorithms. This configuration is most adequate for training several issues: the work flow of the harbour operation, failure management and safety regulations.

This system can be handled both by using a set of controls that emulate the crane control desk or through a set of standard game devices. In this configuration one of the main difficulties that were observed was the perception of depth in the scene. In order to overcome this problem, we have included the use of a tracker that makes it possible to modify the user's point of view perception of depth in the virtual scenery. The use of guidance tools or trackers have been also included, as shown in Figure 10.

4.2 Medium-size system

A step ahead in the complexity of the simulator is the inclusion of a real seat with real crane controls that is located in front of the visualisation system (see Figure 11). This visualisation system is usually compound of a large LCD or plasma or even of a single rear projection screen, although multiple projection screens or monitors can be also arranged to configure several views or a high resolution tiled display.

This system with a single screen can be appropriate for the simulation of quay-side or gantry cranes, since they only need the single front view of the virtual environment to work and do not need to look around.

One of the benefits of this improvement is that stereographic visualisation can be included, since LCD displays now make it possible. In addition, the use of real crane controls helps the trainee to get used to the real working seat, improving his or her response time when using the real machine. This configuration has the drawback, when compared to the desktop system, of being more expensive, requiring more space and permitting the training of only a few operators at a time.

4.3 Fully immersive system

In the fully immersive system, the user is fully immersed in the virtual environment, using a replica of a real crane cabin to which several screens and projectors are attached (see Figure 12). In turn, the cabin is mounted on a motion platform, which makes the user feel acceleration, which is generated by the movements of the vehicle being simulated. The motion effect is a very important factor in immersive environments, since it reproduces the accelerations caused by the real crane, improving, thus, realism and preventing from the motion sickness that is caused by the absence of movement.

Every crane simulator can use this fully immersive system; however, Reach-Stacker and Ro-Ro tractors are particularly suitable for this configuration, since they need a panoramic visual environment in order to drive and manoeuvre along the yard. In addition, as the accelerations of the vehicles are higher than those of the other cranes, a motion platform is especially recommended to avoid simulation sickness.

This configuration involves a higher investment, because it requires a room devoted to the simulators that are installed. However, it yields the possibility of providing a very realistic training that gives the user a considerable increase of his or her skills.

4.4 Input device sensorisation

In order to reduce the difficulties when installing the simulation system in different platforms and configurations, the software system has been made as flexible as possible. When designing the system it was observed that one of the main differences between the

Figure 10 A desktop configuration, with several displays and conventional game devices used as crane controls (see online version for colours)

different systems was the input devices that are used, which range from standard game devices to real crane controls.

Our solution has been to develop a data acquisition I/O board that uses the standard USB interface of the computer and the game devices protocol. By using this board, any hardware device can be turned into an standard game device and be connected to the computer in the same way. On the software counterpart, a programming library makes it possible to configure the

Figure 11 A medium-size system used for training in Guayaquil (Ecuador) (see online version for colours)

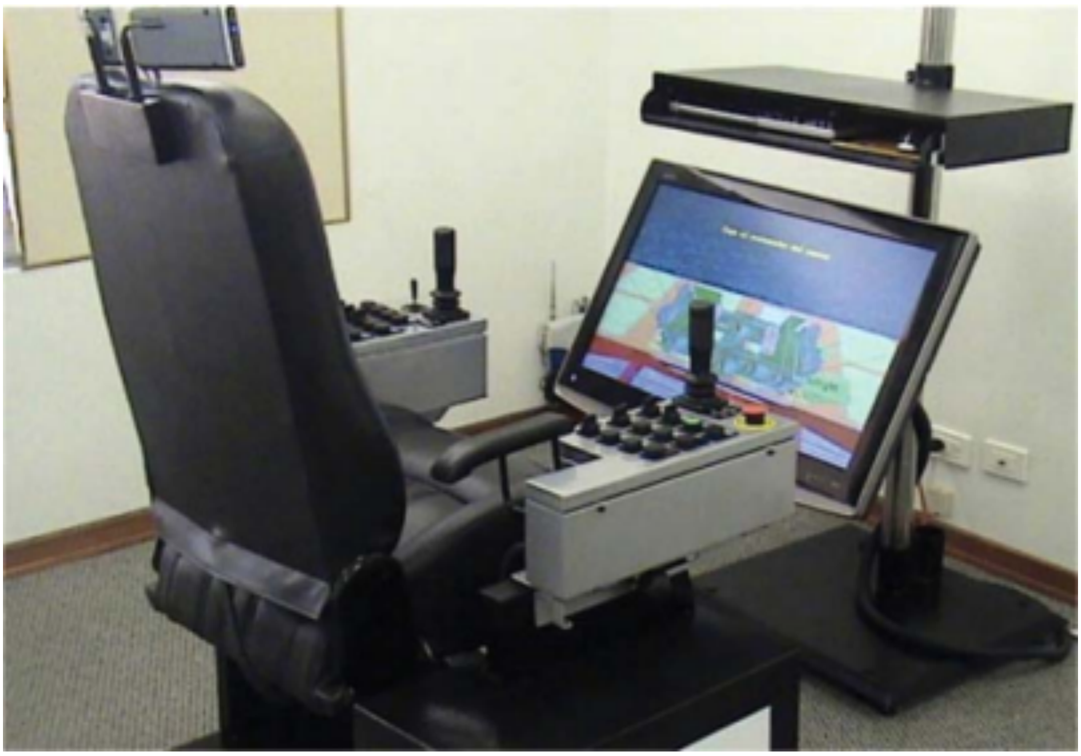
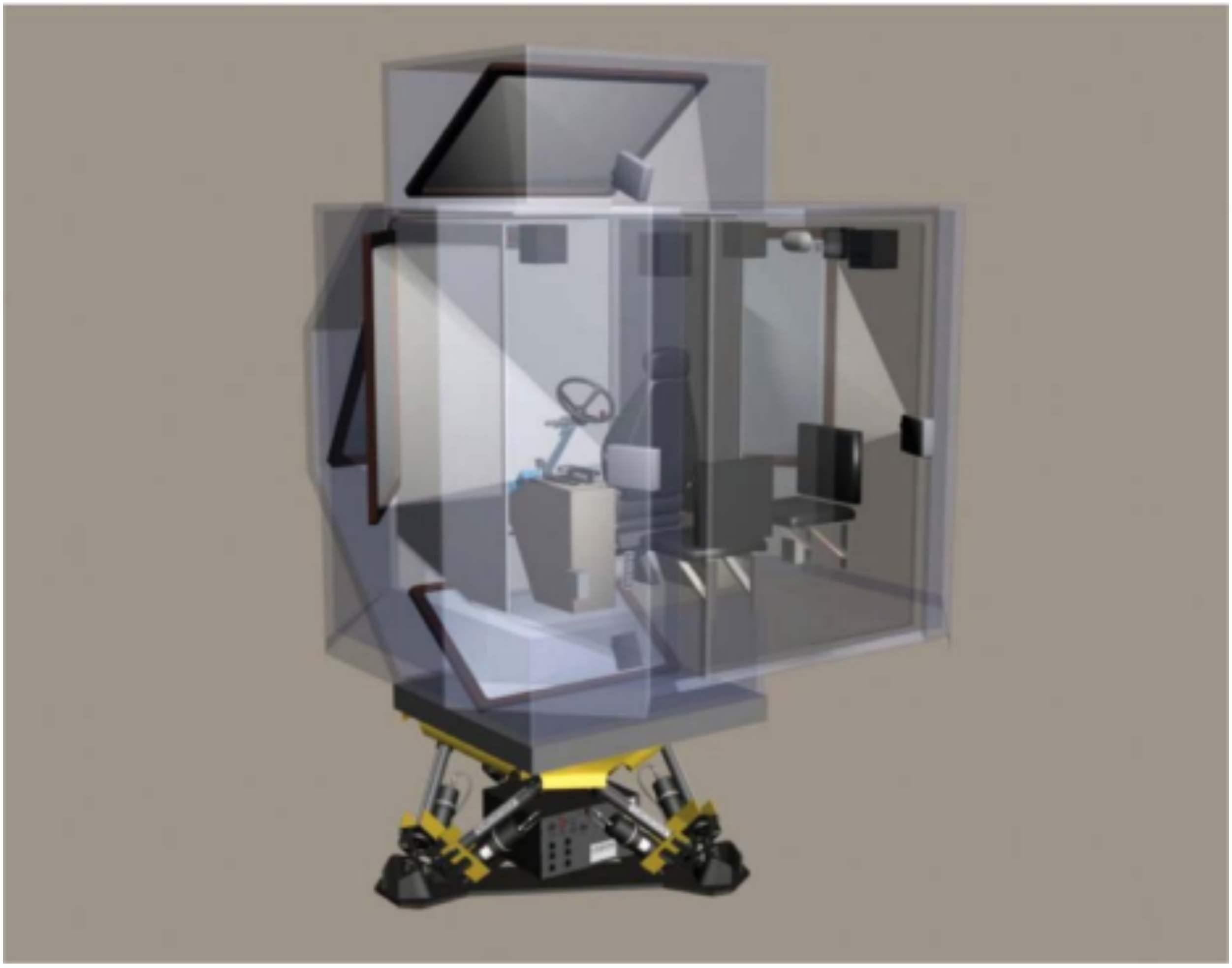


Figure 12 A CAD view of a fully immersive simulation system (see online version for colours)



device assigning labels to the different controls (joysticks, buttons, etc.).

5 Conclusions

This paper presents an overview of the work implemented during the development of a set of harbour training simulators to improve their quality. More precisely, efficient models have been developed for complex systems that, in the past, had not been well reproduced. The design and implementation of training simulators from the hardware point of view has also been analysed, discussing the role that different devices can play depending on the needs of the application. The sensorisation system has been identified as one that requires the highest degree of flexibility if a reconfigurable simulator is desired.

The Training System is currently being used in the Valencia Harbour and in several South American international terminals, and it is in continuous revision by the instructors therein. The main improvements that are currently in progress are the development of an exercise designer and the extension of the physical and mathematical models to improve the realism of the virtual environment. Right now, the simulator can be used only for single user simulations. The use of interoperability standards, such as HLA, will be introduced in the future in order to perform collaborative simulations by utilising several interconnected systems.

Acknowledgements

We would like to thank the many suggestions and recommendations of the reviewers, which have helped to greatly improve the quality and readability of the paper.

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