SHIP-TO-SHORE GANTRY CRANE SIMULATOR DESIGN: CRANE OPERATOR PERFORMANCE ANALYSIS AND ASSESSMENT TOOL OF CAGLIARI UNIVERSITY

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ABSTRACT

This paper describes the ship-to-shore gantry crane simulator developed by authors at Cagliari University. The simulator has been designed and constructed as a means for reducing quayside crane operator error through virtual reality training and investigations, using a physical simulation model. Quayside crane operators in container terminals are increasingly exposed to latent sources of stress because of the continuing advances in This has led to an increasing crane functionality. demand for highly skilled operators in container shipping, a sector that has been experiencing exponential growth for many years now. This work describes the main features and components of the simulator, a transportable containerized facility provided with a 6 degrees-of-freedom motion platform. The simulator has been designed to provide a full immersion environment for high performance training, but also and above all for basic and applied research, monitoring and analysing operator performance by means of electromedical instruments.. The specific activities conducted with the Cagliari simulator (training, research, technological advance) aim to reduce the possibility of accident occurrence, which are largely caused by the onset of fatigue.

Keywords: Ship-to-shore Gantry Crane Simulator, 6 DOF Motion Platform, , HLA Federation, Electromedical Instruments for Performance and Fatigue Assessment

1. INTRODUCTION

Over the last few years container traffic has registered an exponential growth that has resulted in:

- the gigantism trend with container ships of increasingly larger size and capacity, and consequent adaptation of gantry crane design;
- demand for quayside cranes with improved functionality (Fig. 1);
- the need to reduce likelihood of accidents occurring during crane operator task execution.

This has resulted in the need for increasingly skilled gantry crane operators accompanied however by an increase in workplace stress levels creating situations where accidents are likely to occur.

Indeed, in spite of the high degree of automation achieved over the last few years in container handling equipment in general (AGV, Shuttle Carrier etc.), for the ship-to-shore gantry crane, the real "bottleneck" in container terminals, the human operator continues to play a prominent role. Though on the one hand this maintains high levels of employment, on the other it increases the possibility of operator error leading to an accident resulting in injury and/or damage.

This study falls within the area of "activity safety, defined as the discipline that analyses factors influencing operator performance and that studies those processes underlying human error. It encompasses human factors and other branches such as anthropometry and ergonomics.

The causal factors of accidents in transportation systems can commonly be divided into *human*, *technical* and *environmental*. Human error can be the result of improper task and/or equipment design and ineffective training.

The major contributory factors to reducing accident occurrence are enhanced operator skill development, including periodic refresher training to maintain high operational efficiency of quayside crane operators, and performance studies and assessment.



Figure 1: Quay crane unloading sequence from ship to truck

However, actual task performance and fatigue analysis does entail some difficulties, which combined with the challenges of virtual reality training, prompted the idea to set up a simulator that was able to record and analyse performance curves in a virtual environment.

The paper describes the gantry crane simulator conceived and designed by researchers at CIREM, University of Cagliari (D'Errico 2008) jointly with MAST Srl and Genoa University in the frame of the CyberSAR Project - OR13, in collaboration with the COSMOLAB Consortium, and constructed by MISS-DIPTEM, Genoa as a training and research facility for the purpose of analysing and assessing gantry crane operator performance.

2. BACKGROUND AND STATE OF ART

2.1. Ship-to-shore gantry crane operator task

The operator works inside the cab of these giant cranes that travel along the container terminal quayside, loading and unloading containers from the ships using spreaders, that are mechanically connected to the hoist motors via a beam suspended from cables and electrically connected to the crane. The container is hooked/unhooked by means of four corner flippers on the spreader.

The containers are transferred from ship to shore through a combination of two movements (Fig. 1): the spreader-container system is hoisted to the maximum clearance height, and the crane then travels with its load along the bridge rails to the buffer area.

The main difficulty lies in the fact that this operation has to be continuously repeated to move on average over 20 containers per hour, the cab travelling back and forth from the ship to the yard..

Thus throughout the six hour shift the crane operator is exposed both to high vibration, due to cab movements, and to high noise levels generated by the very nature of the operation,. Added to this, is the discomfort caused by the bent forward posture and awkward head/neck positions that the operator is forced to assume to follow the movement of the container some 40 m below.

2.2. Analysis of gantry crane operator performance and fatigue: first results and difficulties encountered

Fatigue, and impaired performance in general, is regarded as a significant factor in the majority of accidents occurring in transport systems (Fadda 1984a). Past research conducted on human fatigue prevention has focused on both the physiological mechanism and on methods for measuring fatigue levels (Sherry 2000; Czeisler 1995; Ji, Lan, and Looney 2002). The most common physiological measurements for determining the extent and length of reduced alterness, considered as an indicator of increased fatigue and/or drowsiness, employ the electroencephalogram (EEG) (Lal and Criag 2002). A training manual prepared by the Transportation Development Centre of Canada in November 2002, provides guidelines for analysing fatigue, drowsiness and the resulting performance deterioration of Canadian navy personnel, combining EEG, EOG (eye movement), ECG (heartbeat) and EMG (muscle tone). Behavioural measurements, that have gained credibility recently, are used to gauge fatigue and are based on the frequency of body movements: the number of movements recorded during task performance over a specific time interval is significantly correlated with the EEG.

Fatigue can also be readily detected by observing facial behaviour: changes of facial expression, eye and head movements, gaze are all indicators of fatigue.

As can be observed from the state of the art review no significant in-depth studies have been conducted concerning port operations, specifically ship-to-shore crane operators. The only data available are those reported by Italian (Colombini, 2006) and Dutch (Huysmans, de Looze, Hoozemans, van der Beek, and van Dieën 2006) researchers on quayside crane operator posture. The Interuniversity Research Centre for Economics and Mobility (CIREM) at Cagliari University has provided two major contributions in this area, providing arousal-performance curves for the gantry crane operators at CICT (Cagliari International Container Terminal), at Cagliari's industrial port. The curves were constructed using the well-known Yerkes-Dodson model (Fadda 1984a), that relates quality of performance with workload. These curves are discussed in two recent papers. The first (Fancello, D'Errico, and Fadda 2007) compares subjective measurements drawn from questionnaires distributed among CICT crane operators - with objective measurements obtained from an actual performance indicator, i.e. the number of containers moved per hour corrected for operator idle time. Accounting for idle times, associated with vehicle coordination within the terminal, allows to properly determine workload during each hour of the shift.

In this way it has been possible to provide the first contribution to actual gantry crane operator performance, establishing a relationship between the curve for perceived fatigue, based on self-assessment, and actual performance measured from hourly container handling data and corrected for idle time for two shifts (afternoon and night). The deviation between performance indicated in terminal operator records and what should be the actual performance curve less idle time, has also been determined..

The second paper (Fancello, D'Errico, and Fadda 2008) concerns an extension of the performance analysis of container terminal stevedores using monthly handling data contained in the data base. (Fig. 2): An average performance curve has been constructed for all the crane operators for each of the four work shifts.

This curve highlighted a number of significant shortcomings concerning the specific job task .

However, numerous problems and shortcomings were encountered in field research when attempting to take measurements without interfering in operators' performance:

- difficulties in determining idle time and the real time recording of environmental parameters inside the crane cab during operation, because of high vibration and noise levels throughout the 6 hour shift;
- conflicts with terminal operability and retrieval of handling data;



Figure 2: CICT crane operators average performance curves for the 4 shifts and corresponding parabolic trend (September 2007)

- disturbances experienced by operator inside the crane cab during task execution;
- inability to determine the influence of boundary conditions on performance: for example with regard to idle time, it was not possible to ascertain whether this affected performance positively (reducing stress and fatigue while crane sits idle) or negatively (decline in alertness and concentration);
- impossibility of analysing changes in operator response to single parameter variations (environmental or boundary conditions).

Added to these limitations are the problems associated with operator training in a real world environment:

- forced waiting times until optimal environmental and boundary conditions are attained;
- prohibitive costs of training infrastructures;
- productive cranes have to be taken out of service for training.

Thus, using a physical simulation model to represent the real world may well be the most suitable and effective solution. The training and research gantry crane simulator at Cagliari University has been conceived for this purpose.

2.3. Physical task training simulators

Task simulators are tools typically used in human factor applications and are an essential ingredient in safety optimisation processes in the transportation sector. They allow to reproduce and assess, also singly, all those factors contributing to fatigue.

The early simulators, that appeared about 40 years ago, were used in aerospace applications by NASA (Fadda 1984b), for the virtual reality reproduction of conditions encountered during the first space missions. In the 1970's they began to be used for military flight training and in more recent years as a research tool for assessing motor vehicle driver fatigue,.

The increasingly skill intensive tasks involved in port operations, such as those executed by ship-to-shore gantry crane operators, have led to the need for training simulators in this area too (Rouvinen, Lehtinen, and Korkealaakso 2005).

Ship-to-shore crane simulators are now commonly used worldwide. Many, largely fixed, simulators owned by container terminal operators are available for training in ports. Others designed and constructed by universities or research institutions are mobile training facilities (containerized) and provide services at terminals. However, generally speaking these simulators are designed for training purposes alone. European ports with gantry crane simulators for operator training include Antwerp (Belgium), Hamburg (Germany), Le Havre and Marseille (France) while around 50 simulators are installed in the United States. All these ports have achieved excellent results in terms of operator training effectiveness, reducing above all times and costs of training compared to training using real cranes

2.4. General description and universal features of ship-to-shore crane simulators

Like existing training simulators, the ship-to-shore simulator comprises five main components :

- 1. operator cab interface (cockpit): a faithful replica of the crane operator workstation, comprising a seat and control console with two iovsticks, one for moving the gantry and the other for spreader-container lifting. It is generally fixed to a **motion platform**, with 2, 3, 4 or 6 degrees of freedom (DOF) depending on load capacity, that not only imparts visual and sound stimuli to the operator, but also stimulates sensations of movement. The platform is supported by actuators placed underneath the cab that move the cab in response both to user input and to the tasks performed. The motion system simulates the vibrations and collisions that occur in real operating conditions;
- 2. **instructor workstation interface**: outside the operator cab, it is equipped with special monitors for following the exercise in real time. The instructor can:
- create innumerable simulation scenarios, in all climatic conditions (wind, rain, sun etc.) and at all times of day (daytime with natural light, night-time with artificial lighting) and for any boundary condition (when selecting different settings a multitude of alternative scenarios can be developed, changing ship and port configuration, as well as equipment employed, like for example different types of spreader);
- make trainees repeat a test in the same conditions, in the event he has not performed well in a particular scenario, and can analyse a posteriori any errors made;
- move on to higher level training, gradually introducing more demanding scenarios as the trainees gradually enhance their skills.
- 3. **visual display system**: recreates through a projection screen the same environment that the operator would actually experience;
- 4. **audio System**: recreates the sound effects generated by vibrations (cab moving during gantry travel), collisions, wind noise;

5. **central operating system:** the simulator "brain", controls operations and executes different simulation scenarios.

Generally, when representing a quayside container crane in virtual reality the focus is either on the visual display system or the motion, with highly advanced platforms. In other cases the emphasis is placed on ergonomics, installing the most technologically advanced cab seats.

The main indicators used for assessing performance level include number of containers handled per hour, number of major and minor collisions, joystick handling (for hoisting and trolley movement), trajectory chosen by the operator versus optimal container trajectory, etc.

2.5. Operator fatigue and performance measurements in physical task simulators

Simulators are increasingly used for researching human factors in transport as these devices allow to reproduce and evaluate, also singly, all those factors contributing to fatigue. In a study conducted at the Northeastern University of Boston (Yang, Jaeger, and Mourant 2006) the behaviour of 12 novice and 12 experienced drivers, recorded during three right-to-left lane change scenarios was investigated. Each lane change involved: 1) a preparatory period; 2) the actual steering manoeuvre from right to left 3) a post lane change period, accomplished maintaining a specific speed. Novice drivers were found to be less secure than experienced drivers, showing significantly more variance in lane position during the preparatory and post-lane change phases. They also spent less time looking at the speedometer and mirrors.

The findings of this study suggest that virtual reality driving simulators may be a useful aid for improving novice driver skills in maneouvres such as lane changes.

One particularly interesting area of human factors is the determination of the visual field using specific devices that identify and record operator gaze points during a work cycle. These applications aim to study the field of vision and the information required by the operator to cope with changing conditions, to determine whether any distractor signals exist that alter perception time and consequently the ability to make the right decision.

The majority of driving simulators (for example the DriveSafety Simulator at the North Dakota State University) are equipped with an oculometer, a gaze tracker that records fixations points and saccades - from the pupil. In addition, with this device it is possible to evaluate, for example, whether any objects outside the field of vision create sources of distraction, thus impairing performance. Recent studies conducted by the Universities of Taiwan and San Diego on the assessment of driver performance interpreting EEGs using fuzzy neural networks (Wu, Lin, Liang, and Huang 2004), have shown that accidents caused by sleepy drivers involve a high percentage of fatalities due to a marked impairment in driver ability to control the vehicle.

3. SIMULATION ARCHITECTURE

The simulation architecture developed by the authors is based on the idea that it is necessary to create a dynamic and flexible framework not only for gantry crane simulation, but even for integrate in further step different equipment in oder to develop a cooperative training; from this point of view the authors decided to develop an innovative federation of simulator interoperating open to redefine the set of entities involved in the scenario; as basic architecture it was decided to use the High Level Architecture (HLA, IEEE Standard and regulation for US DoD Simulators) that allows to interoperate different simulators in an interactive real time framework operating on a distributed network.

The simulator is organized in a real-time Federation composed by different federates, each represent an entity entitled to model some specific element.

The basic object is defined as Actor; currently the general object architecture is based on the structure proposed in figure 3.



Figure 3: Interoperable Object Example

Each object can be owned by a different federate; for the specific case the general structure of federates is proposed in figure 4.



Figure 4: Federation Architecture for the Gantry Crane Simulator

The federation is running over a LAN/WAN (Local Area Network/Wide Area Network) by using RTI (Run-Time Infrastructure) 1.3.7.

The solution proposed allows to create a wide range of alternative configurations for different applications; the federates operates on simple workstation and the federation can run on a single stand alone computer on a single PC to creating a federation of cranes interacting in a networks.



Figure 5: Federates Example for a basic Configuration

Secondary Federates are devoted to manage other entity to interoperate (i.e. a reachstacker Simulator); while observer are used to provide possible reconfigurable workstation for covering different view opportunities; in the proposed case the visual coverage for standard configuration of the gantry crane simulator is 270° horizontal and over 120° vertical, corresponding to a basic cave as proposed in figure 5. The solution proposed is designed to allow dynamic reconfiguration of each PC in order to reallocate the equipments and to create different scenarios; obviously this is in some way limited by the availability of proper hardware device on each Workstation for driving/operating a specific vehicle.

In this project the authors developed basic I/O interfaces in order to guarantee that also by using simple game interface it could be possible to drive many different vehicles, while the gantry crane operation position is based on ad hoc developed motion platform able integrating multiple devices and joysticks. In addition in this case the architecture is designed in order to guarantee possibility to integrate also High Performance Computing Platforms; the project in fact will be used also as pilot to test the possibility complete by distributed processing real-time simulation including very time consuming models such as that ones devoted to consider stress/strain on cables or sea keeping on complex configurations; these models will be elaborated by supercomputing facilities integrated in the federation or substituted by simplified metamodels in case these are not available.

Figure 6 proposes an example of configuration for driving the main gantry crane as well as instructor and secondary positions for other trainees; as proposed in this case the configuration obtained is easy to be adapted by the users.



Figure 6: Federates Example for a basic Configuration

4. SIMULATOR INFRASTRUCTURE FOR CAGLIARI SIMULATOR

The overall structure for the Cagliari simulator is based on the idea to integrate the proposed architecture in a compact complex to be located inside a shelter based on a high cube 40' container. This solution allows to relocate quickly the whole simulator anywhere just by transporting around as a standard container; obviously this decision force to design ad hoc solutions for many systems (i.e. visualization, motion etc.), but guarantee to obtain a very flexible training equipment. considering these aspect the simulator is based on the specific layout corresponding to following main modules:

- Main Gantry Crane Simulator;
- Instructor Station;
- Secondary Stations;
- Plenary Area.

The hardware is based on PC based workstations and laptops; in fact the main gantry crane simulator includes the motion platform and related I/O, sound/vibration control devices and the cave solution with four screens $(2m \times 1.5m)$ covering 4 sides of the cube where the operator is located.

The secondary station are currently based on laptop solution in order to guarantee the possibility to be relocated outside of the shelter if requested for some specific demonstration or training. The secondary stations includes I/O Devices (driving wheels, joysticks etc.); these workstations can be used as dynamic observers by trainee in order to follow the main training session, as concurrent cooperative training platforms or as independent stand-alone scenario for multiple session. By this approach the standard class composed by 8 trainees can be assigned concurrently to real equipment and virtual simulator, allowing to have 4 person concurrently trained on the simulator, 1 on main station and the other one actively operating on secondary positions; respect a traditional simulator this multiplies by 4 the capability of the equipment in term active training time on the simulator for users; at the same time this solution enable the possibility to develop cooperative and competitive training sessions under the supervision of the trainer.

The instructor is located in a specific room in the shelter that enable to control all the environmental conditions (i.e. wind including speed, direction and variations) as well as synchronization with other devices; the instructor is allowed also to activate dynamic review sessions with debriefing capabilities and highlights of errors, collisions and specific events as well as the possibility to visualize interactively in the 3D Virtual framework trajectories (i.e. for the gantry crane spreader).

The Plenary area is based on the concept to be able to reproduce dynamical real-time on-going training sessions or ad hoc debriefing on a framework that allows the instructor to interact in front of the class; the room is equipped with a special smart board that provide the possibility to project a wide representation of the virtual framework with touch screen features including the possibility to put notes and to write over the images.

All the computers operates on a local area network based on RJ-45 that can be connected to external

network; so it becomes possible to setup secondary stations outside of the container and eventually to redesign multiple session with many trainees interacting in the real time simulation.

The solution proposed is open to integrate other models using the FOM (Federation Object Model) and SOM (Simulation Object Model) developed for Cagliari Simulator; due to the conceptual approach in this modeling the architecture can be easily re-configurated in order to include other federates and other objects for creating complex scenarios on Port Operations; considering all these aspect this simulator represent a very innovative and unique solution for port simulation.

5. ELECTROMEDICAL INSTRUMENTS AND ANALYSIS STRATEGIES FOR BASIC AND APPLIED RESEARCH

5.1. Choice of most suitable integrated system of electromedical devices for specific research purposes

In addition to crane operator training, the gantry crane simulator is also a useful tool for conducting both basic and applied research. A research simulator allows to study fatigue and performance of crane operators in a variety of operating conditions by analysing and monitoring objective parameters (EEG, ECG, EMG, EOG plots, etc.), recorded and processed with electromedical devices (Rocca, Bocca, Fadda, Fancello 2007) using known procedures for handling and analysing fatigue test data (performance curves, neural networks). The electromedical devices that will be installed in the Cagliari simulator include: (Fig. 3 shows the final layout of the quayside container crane simulation platform indicating the electromedical devices chosen for research):

- *Eye tracker:* for tracking operator gaze;
- *Dynamic Holter ECG*: for monitoring cardiac frequency;
- *Flicker Fusion Unit* (FLIM): objective test for analysing flicker fusion frequency;
- *Blood Pressure Monitor* (ABPM, Ambulatory Blood Pressure Monitoring):;
- *Digital EEG*: for measuring psycho-physical stress parameter;
- *EMG*: electromyographic tests.

These electromedical devices are used to measure the significant parameters associated with the onset of fatigue in conditions of psycho-physical stress, brought on by complexity of the task itself, and due to the attentiveness required to avoid errors, as well as to exposure to strain and vibrations reproduced by the motion platform.



Figure 7: Cross-section of simulation area and electromedical devices envisaged.

5.2. Psychophysical parameters to be analysed for studying operator fatigue and analysis techniques

In addition to the equipment typically used for fatigue research purposes (EEG, ECG), an eye tracker will also be installed (for tracking operator gaze: at the end of the task a gaze plot is produced showing dispersion of eye gaze points – saccadic eye movements), for studying the visual activities of operators during task execution, discriminating between objects considered to be visual distractions and those regarded as "receptor signals", as vision and visibility are a key human factor in crane operator tasks.

The research strategy for analysing visual activities of ship-to-shore gantry crane operators undergoing simulator training will consist in analysing visual behaviour, measuring, using specific analytic tools (Camilli et al., 2007) or trial analysis, "look zones", fixation points and saccades, in other words the movement between consecutive fixation points (once fixation times/points are known the saccades can be easily detected).

A device for determining muscle tone (EMG test) will also be installed. The system comprises electrodes attached to the body parts to be monitored (neck and back). The electrodes record, display and amplify local nerve response to electrical stimulation and detect muscle anomalies and disorders in particular work postures, providing a measure of operator physical performance.

Some important considerations on awkward and poor posture adopted during task execution, emerged from previous field research on quayside container crane operator stress and fatigue (§ 2.1). In this regard anthropometric measurements (inclination angles) were conducted on crane operators at the Port of Cagliari, as well as task surveys in which operators were asked to what extent, if any, ergonomic factors contributed to fatigue.

As for the ergonomic analysis, the ship-to-shore gantry crane simulator design envisaged a universal attachment for the main platform so as to accommodate a variety of ergonomic workstations and to determine, by changing the type of seat, the psychophysical parameters in different work postures. In this way it will be possible to detect operator muscle disorders, using the EMG test, for different sitting positions. This will contribute to technology advance in the specific sector, creating innovative design solutions for companies collaborating in the research project.

Another electromedical instrument purposely chosen for the Cagliari simulator, after a thorough literature search, is the FLIM unit, that provides a measure of central-nervous system activation (arousal) and of the level of performance (memory, attention, reaction time).

The reaction time of an individual to light stimulus, measured using FLIM, provides an indicator of the level of performance of quayside container crane operators, given the importance in task execution of visual activities and the degree of precision to be achieved for focusing on the target (latching the container onto the spreader some 40-50 m below and transferring it from ship to quayside).

FLIM validity criteria have been addressed in a study (Daniel, Fabry, and Fickova 1985) investigating the effects of shift work. The authors have been able to demonstrate that the individuals examined adapt far more quickly to work conditions at the subjective psychological level, as emerged from the questionnaire responses, than at the psycho-physiological level, indicated by the FLIM measurements.

The particular simulation architecture of Cagliari's gantry crane simulator (HLA federation), allows for the inclusion of electromedical equipment as federates. The simulation system provides advanced synchronization functionality ensuring that the psychophysical fatigue measurement systems can be combined with simulated time evolution. The debriefing system matches the operating phases with those portions of the electromedical plots whose spectra coincide with fatigue phases. A model such as a neural network (NN) model will be used for reading and interpreting the complex data

In this sense it will be possibile to construct performance curves on the simulator along the same lines as for field measurements.

6. CONCLUSIONS AND FUTURE RESEARCH

This paper describes Cagliari University's ship-to-shore gantry crane simulator. This simulator is an essential tool for better understanding the underlying causes of accidents incurred by container crane operators who are exposed to increasing levels of stress for the reasons described in the introduction. Indeed, fatigue and performance assessment through psychophysical parameters monitoring with electromedical devices is instrumental in reducing the likelihood of accidents.

Thus research and training activities conducted with the simulator will be of key importance. The development and management strategies will be decisive for organising and promoting Cagliari's quavside container crane simulator in order to attract potential clients to the training facility (e.g. container terminal operators). Training and refresher courses for container crane operators using the Cagliari simulator are important for two reasons. In economic terms the proceeds from training package sales to terminal operators will be used to fund research activities. Therefore management strategies need to be created for competitive advantage, offering up-to-date training packages at attractive prices. In this sense one strong point of the Cagliari simulator is its transportability. The second reason is that the data recorded during training sessions will be used to build up a database for use in research

Lastly, concerning future research lines, the shipto-shore gantry crane simulator has been developed within a broader research project aimed at setting up a network of simulators to be located in a number of areas in central-southern Italy (cyberinfrastructure). This infrastructure will make it possibile to carry out integrated task training, by means of remote experimentation and tests coordinated by an efficient training network. The integrated multimedia programme also envisages the construction of a container trolley simulator. In addition the proposed approach guarantee the possibility reuse and further develop for the simulator new application areas such as operative and safety policy design, re-engineering and validation, terminal analysis and control etc.

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