A CYBER-PHYSICAL GAMING SYSTEM FOR VOCATIONAL TRAINING

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ABSTRACT

Cyber-physical systems enable new digital ecologies in industrial and workplace lifelong learning. This paper reports on early efforts in delivering a virtual environment and system for vocational education and training (VET), in particular targeting the needs of craft and trade skills. The domain of stone masonry is presented herein, where its underpinning activities are learning through virtual environments, simulation and role play. The challenges are not only the synchronicity between physical and software components but also the in-game mechanics that incorporate building blocks of effective training and skills development strategies. A prototype body-area sensor network in a cyber-physical game environment demonstrates the interaction between virtual objects and the player-learner.

INTRODUCTION

Situating learners in a context that mimics realistic working conditions is paramount for learning in a digital environment. Serious Gaming environments are designed to engage a player through immersive content in conjunction with game-play mechanics. It is this nature of game systems that this work seeks to exploit; to take advantage of situational awareness of content and of context.

In the last decade, Virtual Environments and Systems (VES) have witness its inception as novel education technology. This drive now sees a host of kick-starters and crowd-funded generation of innovators and disruptors in VES as the future of education. The next generation of Ed-Tech is already here, combining the fun of gaming with augmented reality [1].

At least for Vocational Education and Training (VET) there are comparatively fewer VES technologies for education than for Science, technology, engineering and mathematics (STEM) education. VET poses many challenges. National funding in Further Education for which VET falls under has not received the same level as tertiary education. From a practical and cost perspective, a VR-based solution for VET means providing a more affordable entry given the often-high capital costs of simulation labs. VET is unique in its programmes since students regularly transit between classroom and workplace (on the job learning). Thus, from a user perspective, a VET VES has to be well balanced in addressing the needs of the trainers, module management, feedback, interaction, monitoring, etc. Indeed, VET VES could be instrumental in enhancing the quality and consistency of apprenticeship training provision which has been a concern in numerous UK government reports over the past decade. Most recently the UK Parliamentary ‘Apprenticeship Inquiry 2016’ highlighted the need for Quality Assurance of apprenticeship training to ensure that minimum standards can be enforced. Not only does VET VES present an opportunity for QA & modernising apprenticeship training, but also it could make the pursuit of an apprenticeship more attractive to millennials and thereby helping towards alleviating the perennial problem of skills shortages in the Repair and Maintenance (R&M) sector [2], [3].

This paper reports on one initiative of the BEACONING (Breaking Educational Barriers with Contextualised pervasive and game-full learning) project [4] to develop a VES solution for VET. Central to the BEACONING platform are gamified lesson plans that take advantage of VES. The challenge pertains to creating a cyber-physical game system (CPGS) for vocational training, particularly for on-site construction practice involving portable power tools. It should be noted that there is

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currently no formal training provision of power tools in VET colleges in Scotland. Therefore, our proposed VET VES address a clear gap in current training provision whilst employing cutting-edge digital technologies. The trainee’s needs are met through features such as module access, workflow profiling, personalized assessment and supplemental content. Such a CPGS is intended to mitigate risk, trainee/trainer anxiety, mistakes including staff and equipment requirements (e.g. health and safety) in traditional simulation labs.

**A CPGS FOR STONEMASONARY TRAINING**

Stonemasonry requires operating hand and power tools, as such this vocation is exposed to potentially fatal accidents throughout the course of using the tool. One tool in particular is the portable power grinder at construction sites. Statistics on machine tool injuries in the UK construction sector is an alarming 80% [5] while the OSHA [6] cites some 400,000 annual emergency room visits per year.

VES configured as VR training platforms for tasks are well-established in medical and rehabilitation, sports, and industrial work. All offer some form of interaction and manipulation of virtual scenes. There is also a growing number of Serious Games that exploit Mixed Reality (MR) technologies. MR includes a wide range of devices such as see-through Head Mounted Displays (HMD), mobile devices, multi-touch tables, or even tangible interfaces that control or represent virtual information. Few however readily offer plug-and-play with CPGS or are able to satisfy the needs for VET.

An ideal VES for stonemasonry training requires interaction and visualisation, content that is relevant, and an immersive workspace to facilitate learning and transfer of skills. Relevance, facilitation and transfer must align with real world interaction to build stone engineering competencies, and this is best when real power tools can serve as proxies to the VE.

As a case in point, angle grinders and polishers for on-site stone replacement and stone carving, has allowed stonemasons to speed up the process of the work. An angle grinder disc rotates at about 10,000 rpm. Allied with the weight of the machine and speed of rotation of the disc, they must be held with both hands: one on the hilt and the other on the body of the machine. Recent research highlighted poor practice with the inappropriate application of such power tools results in damage to buildings e.g. surface scratching/gouging, enlargement of beds and joints etc. [7]. Moreover, there are several work-force health and safety issues to consider. For stonemasonry, workplace activities such as cutting, grinding and polishing materials that contain respirable crystalline silica produce fine dusts and are associated with an increased health hazard. In addition, there is a high prevalence of work-related musculoskeletal disorders; stonemasons continually work in awkward postures during stone-cutting, consequently, they suffer from discomfort in different parts of their body, specifically in the lower back, knees and shoulders [8].

Therefore, it is important to evaluate modern work practices and their biomechanical impact prior to recommending them as superior to existing practices [9]. These inherent dangers of stonemasonry practice can be prevented with changes in work equipment or work practices, combined with occupational hygiene preventive and protective measures underpinned by appropriate training for both workshop and field-based tasks [10].

Many of these aspects cannot be replicated in a pure VES or a Serious Game. However, through a CPGS this can become possible. The integration of VES, Serious Games and CPGS signifies a major step in skills training and education in a multimodal VES platform. Interaction is supplemented by the real-time sensing capabilities, visualisation is enriched by game content, and the game mechanics situates the trainee in the content and context. Though not the scope of this paper, Fig 1 presents an abstract framework that will be used in the CPGS design to map leaning mechanics to game mechanics interaction [11]. Learning mechanics represent the pedagogical activities while game mechanics are the elements to deliver stimulating game-play. For the purpose of VET, the combined problem-based experiential learning is through a mixed-reality world, i.e. a virtual environment with some capacity to include the physical workspace and corresponding simulations, or vice versa. The learning mechanics (e.g., tasks, activities, goals, relationships) and game mechanics (e.g. quests, dashboards, goals, levelling, role-play, tokens, etc.) are mapped to create a flow of actions to obtain higher-order skills; the transitions between task-centred learning and cognitive learning. Unlike existing educational media and teaching tools the proposed CPGS encourages trainees to play an active role in their own learning, since outcomes will dynamically change depending on their input.

Technology trends are bringing to bear the crossings of pervasive VES technologies and gamification. The CPGS rides this trend, where its modus operandi also serves to further the understanding of the effects on how pervasive gaming affect people with low-to-medium skill level to end-user education and training designed to enhance the culture of curative and independent learning within a vocation [12].
CPGS ARCHITECTURE

The CPGS is primarily built using the UbiITS framework [3], [13]. Wireless inertial sensors (accelerometer, gyroscope and magnetometer) are used to capture the motions of tools, accessories and the worker’s body. In addition to the motion tracking sensors the CPGS comprise a checklist interface that conforms to health and safety field requirements, power tool handling activities, ergonomics and a real-time VR game. In-house developed wireless sensors are operated on the 2.4 GHz proprietary RF and capable of streaming samples at variable rates. Sampling rate for this application was set to 32Hz. Data streaming and commands issued to the sensors were programmed to be compliant to the UbiITS framework, which allowed tight coupling of the sensors with the software algorithms and event triggering routines. The central receiver is a standard PC application, which can also run in a single board computer that runs Windows or Linux. The receiver connected to the wireless sensors with a RF circuitry similar to the ones present on the sensors, simultaneously running the main application and connecting to the cloud, e.g. the BEACONING cloud platform Fig 2.

Fig 1. Mapping Learning Mechanics to Game Mechanics [11].
MULTI-LAYERED EVENT PROCESSING NETWORK

The motion sensors were programmed in the firmware to stream data in various levels of granularity: raw measurements (i.e. acceleration, angular rate, and heading), orientations (absolute global orientations or inclination) or various processed events (e.g. held upright, held flat, on-the-move, static, vibrating). Complex events were further recognised by combining events from multiple sources. An example for a complex event detection associated with safety helmet and respiratory mask is described in Fig 3. Multi-layered event processing and filtering offers the capability to detect complex events at various levels with reduced chances of false positive detections. Sophisticated logic is implemented to prevent trainees from deceiving the system, for example not wearing the appropriate Personal protective equipment (PPE) and trying to make the system to believe it is worn. The rigor of the action detection can be always improved by utilising hardware with advanced sensing capabilities. For instance, instead of relying on the motion/orientation sensors, a galvanic sensor integrated in the respiratory mask can certainly provide improved results in detecting whether it is worn, or not. However, this requires a new peripheral hardware design with appropriate electronics integrated. Alternatively, the multi-layered event processing approach used here enabled processing complex events with cheap instrumentation.

CHECKLIST/SELECTION INTERFACE

In addition to the automatic event processing a checklist/selection based interface was also provided to the user. This interface collects the following rudimentary information and interacts with the user using various messages and pop-ups.
1. Appropriate PPE worn (safety helmet, safety boots, Gloves, Ear defenders etc.)
2. Appropriate RPE worn (FP3 level respiratory mask)
3. Carry out a pre-work area check
4. Work area is regularly inspected
5. Machine check
6. Correct selected blade
7. Waste removal procedure planned
8. Pre- and post-job protocols (warm-up and warm-down after body muscles)
9. Work phase - Comply with task specific method statement + risk assessment
The game content designed for stonemasonry training embeds protocols for Health and Safety (H&S). These protocols are represented via a checklist (e.g. yes/no answer) or validated through activities or tasks interactions in the CPGS. For example, selecting the correct blade size and type was performed by a selection list based interface that lists out standard blade configurations and stone types where the user was able mix and match compatible options.

Fig 4. Data flow of the CPGS from the sensors to the virtual reality

Fig 5. A sequence of virtual cutting process, a tangible grinder interfaced to a virtual blade
UNITY 3D ENABLED CPGS

Fig 4 shows the data flow from the sensors through various processing blocks and the text/selection based interface. The virtual environment caters two aspects of cutting and material removal process as described below.
1. Planning – User will plan the cutting path, sequence, required number of passes, cutting depth, orientation of the stock and the tool, etc. System will assist his actions with its snapping and quick sketching features.
2. Experiencing – User will experience the cutting process similar to a real-life setting. The time taken for this simulated experience is expected to be comparable and translatable to the time required to complete the process in real-life setting. Physical feedback and vibrations are also anticipated to have sufficient resolution to the cutting process. No virtual object snapping will be available in this mode to ensure untethered manipulation in the virtual environment and that is fully controlled by the user’s movements.

The virtual environment under development uses the Unity3D engine (Fig 5). Unity gaming provides various modules by default for loading and rendering 3D mesh models. Furthermore, features from unity engine such as, lighting effects, collision detection and physics were used. Various scripts for object manipulation/interaction and real-time Boolean operations (i.e. material removal) were developed to extend the unity framework’s functionality.

DISCUSSION

The system was developed as a bespoke solution for stonemasonry. However, the fundamental CPGS and the technical infrastructure behind this are generic and applicable and reusable in other scenarios which involve high dexterity physical tasks. For example, the same system can be recycled for other applications such as sculpting, surgical procedures, welding, soldering, painting, etc. by simply reloading the content and reconfiguring the logics.

The system can further be used as tool to measure and evaluate the performance of the user and the quality of the work. For instance, in terms of a stone cutting process metrics such as accurateness of trajectory-following, number of passes used, choice of chuck sizes, appropriateness of followed cutting sequence, dimensional tolerances of the final product, compliance with H&S standards can be employed. The data required for establishing these metrics can be extracted from the system and then processed as required. This enables the system to provide an objective feedback on the aforementioned performance criterial.

Furthermore, it provides the opportunity for the trainee to practice in a safe working environment until they master the activity which is paramount for quality assurance and maintaining training standards. It can be an intermediary step for trainees to experience the workflow before they enter into the practical on-site work.

The system can run both in (1) simulation only mode where the actual cutting is only performed in the virtual world and (2) parallel-world mode where the system duplicates the actual process which is useful to acquire the performance metrics.

CONCLUSION

While the current system is used to prove the validity of the overall conceptual idea the technical architecture still requires various improvements to the lower level details, particularly the physical hardware and its control. The grinder needs to be outfitted such that it serves as a tangible interface. Its accompanying software control has to facilitate interplay between the cyber, physical and behavioural aspects of the system. The event-based controller currently under development should enable state feedback for parameter changes within the VR simulation. An off-the-shelf power grinder is being reversed engineered to include the necessary sensing capabilities, including features such as bidirectional control, automatic safety locking, braking etc. The cutting blade on the grinder is removed for safety reasons. However, the gyro effect created by the spinning mass and the kickback generated when the blade engages with the stone are two vital aspects experienced in real-life settings that need to be emulated to a sufficient resolution to achieve context association. One proposed solution is integrating a well-shielded spinning mass, essentially an eccentric drive, as a compromise to address safety concerns while providing near realistic experience.

The VR simulated cutting currently rendered in Unity will be improved. In its present development, the Boolean computation budget is too high compromising the frame rate resulting with high latency graphics and physics rendering. Real-time performance and latency issues will be very critical when the human-in-loop simulations are performed in the physical world. This requires bespoke high performance procedural mesh modification and regeneration algorithms instead of the basic mesh operations performed in the current system. Various multi-threading and graphics processing unit (GPU) based parallel approaches are to be further explored for this purpose. Although this is a complicated and challenging process previous works in this area have highlighted the possibility of achieving promising results.

ACKNOWLEDGMENTS

The work presented herein is partially funded under the European H2020 Programme BEACONING project, Grant Agreement nr. 687676.

REFERENCES

[1] M. Dunleavy and C. Dede, “Augmented Reality Teaching and Learning,” in Handbook of Research on Educational Communications and Technology, J. M. Spector, M. D. Merrill, J. Elen, and M. J. Bishop, Eds. New York, NY: Springer New York, 2014, pp. 735–745.
[2] M. Abdel-Wahab, “Rethinking apprenticeship training in the British construction industry,” *J. Vocat. Educ. Train.*, vol. 64, no. 2, pp. 145–154, Jun. 2012.

[3] A. Sivanathan, M. Abdel-Wahab, F. Bosche, and T. Lim, “Towards a Cyber-Physical Gaming System for Training in the Construction and Engineering Industry,” in *ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2014, p. V01BT02A034–V01BT02A034.

[4] “EU H2020 Project BEACONING,” *EU H2020 Project BEACONING*, 09-Feb-2017. [Online]. Available: http://beaconing.eu/.

[5] “Health and safety in construction sector in Great Britain 2014/15,” 2016.

[6] United States Department of Labor, “Accident Search Results Page | Occupational Safety and Health Administration.”

[7] S. McGibbon and M. Abdel-Wahab, “Stonemasonry skills development: two case studies of historic buildings in Scotland,” *Struct. Surv.*, vol. 34, no. 3, pp. 218–241, Jul. 2016.

[8] S. Gangopadhyay, B. Das, T. Das, G. Ghoshal, and T. Ghosh, “An Ergonomics Study on Posture-Related Discomfort and Occupational-Related Disorders Among Stonecutters of West Bengal, India,” *Int. J. Occup. Saf. Ergon.*, vol. 16, no. 1, pp. 69–79, Jan. 2010.

[9] J. A. Hess, R. L. Mizner, L. Kincl, and D. Anton, “Alternatives to lifting concrete masonry blocks onto rebar: biomechanical and perceptual evaluations,” *Ergonomics*, vol. 55, no. 10, pp. 1229–1242, Oct. 2012.

[10] J. Vedder and E. Carey, “A multi-level systems approach for the development of tools, equipment and work processes for the construction industry,” *Appl. Ergon.*, vol. 36, no. 4, pp. 471–480, Jul. 2005.

[11] S. Arnab et al., “Mapping learning and game mechanics for serious games analysis: Mapping learning and game mechanics,” *Br. J. Educ. Technol.*, vol. 46, no. 2, pp. 391–411, Mar. 2015.

[12] J. M. B. Hauge, T. Lim, M. Kalverkamp, F. Haase, and F. Bellotti, “Analysis on Educating Mechanical Engineers Through Serious Games Using Pervasive Technologies,” in *ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2016, p. V01BT02A050–V01BT02A050.

[13] A. Sivanathan, “Ubiquitous Integration and Temporal Synchronisation (UbiITS) Framework – A solution for building complex multimodal data capture and interactive systems,” Doctor of Philosophy, Heriot-Watt University, Edinburgh, Scotland, UK, 2014.