

Towards a Mixed Reality System for Construction Trade Training

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5 Abstract

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6 Apprenticeship training is at the heart of government skills policy worldwide. Application of 7 cutting edge Information and Communication Technologies (ICTs) can enhance the quality 8 of construction training, and help in attracting youth to an industry that traditionally has a 9 poor image and slow in up-taking innovation. We report on the development of a novel 10 Mixed Reality (MR) system uniquely targeted for the training of construction trade workers, 11 i.e. skilled *manual* workers. From a general training viewpoint, the system aims to address 12 the shortcomings of existing construction trades training, in particular the lack of solutions 13 for enabling trainees to train in realistic and challenging site conditions whilst eliminating 14 Occupational Health and Safety risks. From a technical viewpoint, the system currently 15 integrates state of the art Virtual Reality (VR) goggles with a novel cost-effective 6 degree-16 of-freedom (DOF) head pose tracking system supporting the movement of trainees in room-17 size spaces, as well as a game engine to effectively manage the generation of the views of the 18 virtual 3D environment projected on the VR goggles. Experimental results demonstrate the 19 performance of our 6-DOF head pose tracking system, which is the main computational contribution of the work presented here. Then, preliminary results reveal its value to enable 20 21 trainees to experience construction site conditions, particularly being at height, in different 22 settings. Details are provided regarding future work to extend the system into the envisioned

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- 23 full MR system whereby a trainee would be performing an actual task, e.g. bricklaying,
- 24 whilst being immersed in a virtual project environment.
- 25 Keywords: Apprenticeship; construction; trade; training; mixed reality; occupational health
- 26 and safety; work at height; productivity monitoring.

27 Introduction

Given the on-going development in new technologies (such as, Building Information Modelling (BIM) and green technologies), investment in training becomes essential for addressing the industry's evolving skills needs. It is also imperative to ensure that there are sufficient numbers of new entrants joining the construction industry to support its projected growth. Latest figures from the UK Office of National Statistics (ONS) reveal a 2.8% growth in the third quarter (Q3) of 2013 (ONS, 2013). A sustained investment in construction apprenticeship training thus becomes essential.

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In the UK, the Construction Industry Training Board (CITB) retains a unique position by 36 37 administering a Levy/Grant scheme (LGS) on behalf of the construction industry - as 38 mandated by the Industrial Training Act 1964. It raises approximately £170m annually from 39 training levies which is re-distributed to the industry in the form of training grants. 40 Approximately 50% of the levy is spent on training grants for apprenticeships in order to 41 attract, retain and support new entrants into the industry. However, the UK Government's 'Skills for Growth' white paper similarly called for: 1) Improving the quality of provision at 42 43 Further Education (FE) colleges and other training institutions, and 2) Developing a training system that provides a higher level of vocational experience; one that promotes a greater mix 44 of work and study (Department for Business, Innovation and Regulatory Reform, 2009). And 45 46 recently, the UK Minister for Universities and Science, David Willetts, announced the 47 introduction of tougher standards to drive up apprenticeship quality -a view which was 48 echoed by the Union of Construction, Allied Trades and Technicians (UCATT) (BIS, 2012; and Davies 2008). 49

50 Globally, the International Labour Organization (ILO) urges governments worldwide to 51 upgrade the skills of master crafts-persons and trainers overseeing the apprenticeships and 52 ensure that apprenticeships provide a real learning experience (ILO, 2012). Clearly, 53 enhancing the quality of apprenticeship training in-line with the industry's evolving skills 54 needs is paramount for supporting its future development and prosperity.

Along with other researchers and experts, we argue that novel technology can enhance trainee 55 56 experience, improve training standards, eliminate or reduce health and safety risks, and in 57 turn induce performance improvements on construction projects. For example, simulators for 58 equipment operator training allow testing trainees to ensure that they can demonstrate a 59 certain skill level prior to start working. A company developing novel technologies for the 60 mining industry has claimed that, as a result of using simulators, there was a 20% 61 improvement in truck operating efficiency and reduction in metal-to-metal accidents 62 (Immersive Technologies, 2008).

Yet, the construction industry has been traditionally slow in the uptake of innovation,
particularly in areas such as ICT (Egan Report, 1998). For this reason, innovation in
construction continues to be at the top of the UK government (UK Government, 2011; UK
Government, 2013).

We report on the development of a novel Mixed Reality (MR) system using state-of-the-art Head-Mounted Display (HMD) and 6 Degree-Of-Freedom (DOF) head motion tracking technologies. The overarching aim of the MR system is to enable construction trade trainees to safely experience virtual construction environment while conducting real tasks, i.e. while conducting real manual activities using their actual hands and tools, just as they currently do in college workshops. Figure 1 illustrates the concept of the MR system where the trainee experiences height in a virtual environment whilst performing the task of bricklaying.

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Figure 1: Illustration of the use of the proposed MR environment to immerse trainees and their work within a
"work at height" situation. Here the trainee conducts bricklaying works on the floor of the college lab (safe), but
experiences conducting the activity on a high scaffold (situation with safety risks).

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79 The piloting of our MR system mimics working at height in a construction site environment. 80 We focus on height simulation as falling from height accounts for nearly 50% of the fatalities 81 in the UK with falls from edges and opening account for 28% of falls, followed by falling 82 from ladders (26%), and finally scaffolding and platforms (24%) (HSE, 2010). Similarly, in 83 the USA, the most common types of falls from heights in the construction industry are falling 84 from a scaffold and ladder (Rivara and Thompson, 2000). The construction sector is 85 particularly impacted because many construction-related trades involve working at height, such as scaffolders, roofers, steel erectors, steeple-jacking, painting and decorating. 86 87 Furthermore, ironically for H&S reasons, colleges can often not train trainees at heights 88 above 8m. We are hoping that our system enhances the quality of training provision by 89 providing trainees an exposure to construction site conditions through simulation, so that they 90 are better prepared to working on site and the likelihood of accidents is reduced (through 91 better perception of hazards on site).

The paper commences with a literature review of the current applications of MR in construction training, which leads to identification of the need for different MR systems better suited to the needs of construction trade training. We then present the on-going development of such an MR system. The current system is only a VR system, but includes several of the functional components that will be required in the final MR system. We particularly focus on our main computational contribution that is a robust, cost-effective 6-

98 DOF Head Tracking system. The performance of the current system is experimentally 99 assessed in challenging scenarios. Finally, strategies are discussed for the completion of the 100 envisioned MR system.

101 'Reality-Virtuality' continuum of construction training

Figure 2 depicts a 'Reality-Virtuality' continuum in the context of construction training, highlighting the training environments where construction training takes place. This section summarizes developments that have been made at different stages within this continuum, starting with training in real environments, followed by training using Virtual Reality systems, and finally training using Mixed Reality systems.

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108 Figure 2: Reality-Virtuality Continuum in the context of construction training ().

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110 Real Environment

At one end, there is training within '*Real*' construction project environment. For example, the UK CITB has set-up the National Skills Academies for Construction (NSAfC) with the aim of providing project-based training that is driven by the client through the procurement process. NSAfC included projects such as the 2012 Olympic which provided 460 apprenticeship opportunities.

However, training on real construction projects is constrained by the type of activity taking place on site, project duration, in addition to (occupational) health and safety (H&S) risks.
Trainees may not be allowed to perform certain tasks on real projects as this can cause delays and errors can be costly, especially when it comes to high profile projects such as the Olympics. To address this issue, attempts have been made in recent years to 'simulate' real project environments where trainees can conduct real tasks without compromising project performance and H&S.

An example is 'Constructionarium' in the UK which is a collaborative framework where university, contractor and consultant work together to enable students to physically construct scaled-down versions of buildings and bridges (Ahearn, 2005). This enables students to experience the various construction processes and associated challenges that cannot be learned in a traditional classroom setting. Auburn University in the US, and the University of Technology Sidney in Australia have run similar schemes (Burt, 2012; Forsythe, 2009).

As for construction trade training, apprentices typically train in a FE college's workshop. The FE college training counts towards their attainment of a vocational qualification, which also includes work placement. However, it must be noted that training at FE's workshop is constrained by the space provided at the college and the requirements set-out in the National Occupational Standards – whereby trainees can only experience heights up to 8m, which is not representative to working at higher heights on many construction projects, such as highrise buildings or skyscrapers.

136 Virtual Reality (VR)

At the other end of the 'Reality-Virtuality' continuum (Figure 2), *Virtual Reality* (VR) is increasingly used for construction training. VR development boomed in the 1990's and VR is in fact still under intense development, with education and training an important area of application. Mikropoulos and Natsis (2011) define a Virtual Reality Learning Environment (VRLE) as "*a virtual environment that is based on a certain pedagogical model, incorporates or implies one or more didactic objectives, provides users with experiences they would* 143 otherwise not be able to experience in the physical environment and can support the 144 attainment of specific learning outcomes."

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146 VRLEs must demonstrate certain characteristics that were summarized by Hedberg and 147 Alexander (1994) as: *immersion*, *fidelity* and *active learner participation*. Other terms 148 employed to refer to these characteristics are *sense of presence* (Winn and Windschitl, 2000) 149 and *sense of reality*.

150 VRLEs can be classified as: *Desktop*, where the user interacts with the computer generated 151 imagery displayed on a typical computer screen; or *Immersive*, where the computer screen is 152 replaced with a HMD or other technological solutions attempting to better 'immerse' the 153 participant in the (3D) virtual world (Bouchlaghem et al., 1996). Most current simulators are VRLEs that are commonly developed for *plant operation training* (e.g. tower cranes, 154 155 articulated trucks, dozers and excavators). For example, Volvo Construction Equipment 156 (Volvo CE, 2011) and Caterpillar have developed simulators for training on their range of heavy equipment, such as excavators, articulated trucks and wheel loaders (Immersive 157 158 Technologies, 2010).

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Equipment simulators enable training in realistic construction project scenarios with highfidelity, which is made possible by force feedback mechanisms, and without exposing trainees or instructors to occupational H&S risks. They support fast and efficient learning thereby increasing trainees' motivation (Volvo CE, 2011; TSPIT, 2011). For example, the ITAE simulator, employed in mining equipment operation training, is used to ensure that apprentices can demonstrate a certain skill level prior to working in mines. The manufacturer claims that the simulator has proved to be effective in modifying and improving operators' behaviour as well as enhancing the existing skills levels and performance of employees(Immersive Technologies, 2008).

169 VRLEs have also been developed for supervision/management training. The first UK 170 construction management simulation centre has opened at Coventry University in 2009 and is 171 known as ACT-UK (Advanced Construction Technology Simulation Centre). The centre is aimed at already practicing foremen and construction managers, and potentially students 172 173 (Austin and Soetanto, 2010; ACT-UK, 2012). Similar centres exist with the Building 174 Management Simulation Center (BMSC) in The Netherlands (De Vries et al., 2004; BMSC, 2012) or the OSP VR Training environment collaboratively developed as part of the 175 176 Manubuild EU project (Goulding et al., 2012). In these VRLEs, trainees can be partially 177 immersed in simulated construction site environments to safely expose them to situations that 178 they must know how to deal with appropriately. These may include H&S, work planning and 179 coordination, or conflict resolution scenarios (Harpur, 2009; Ku, 2011; Li, 2012). Other 180 VRLEs have also been investigated for other applications for enhancing communication and collaboration during briefing, design, and construction planning (Duston, 2000; Arayici, 181 182 2004; Bassanino, 2010).

VRLEs can generally provide significant benefits over traditional ways of training and learning. The main benefit is to enable trainees to "*cross the boundary between learning about a subject and learning by doing it, and integrating these together*" (Stothers, 2007). A simulated working environment enables skills to be developed in a wide range of realistic scenarios, but in a safe way (Stothers, 2007; Austin and Soetanto, 2010).

188 Nonetheless, despite the general agreement on the potential of VRLEs to enhance education, 189 Mikropoulous (2011) and Wang and Dunston (2005) noted that there is a general lack of 190 thorough demonstration of the value-for-money achieved by those systems, which may be due to implementation cost, but possibly also to the quantity and quality of training scenariosthat could be developed and their impact on learning and practice.

It is interesting to note that VRLEs and Constructionarium are two learning approaches at the opposite ends of the continuum and may be regarded as complementary. Arguably, a blended learning approach can be employed whereby VRLEs are used for initial learning exercises, and approaches like Constructionarium are used for subsequent more real learning-by-doing activities and thereby supporting the transition before going on-site.

198 Mixed Reality (MR)

199 Within the Reality-Virtuality continuum, Mixed Reality (MR), sometimes called Hybrid 200 Reality, refers to the different levels of combinations of virtual and real objects that enable 201 the production of new environments and visualisations where physical and digital objects co-202 exist and interact in real time (De Souza e Silva and Sutko, 2009). Two main approaches are 203 commonly distinguished within MR. Augmented Reality (AR) specifically refers to situations 204 when computer-generated graphics are overlaid on the visual reality, while Augmented 205 Virtuality (AV) specifically refers to when real objects are overlaid on computer graphics 206 (Milgram and Colquhoun, 1999).

MR has a distinct advantage over VR for delivering both immersive and interactive training scenarios. The nature and degree of interactivity offered by MR systems can provide a richer and superior user experience than purely VR systems. In particular, in contrast to VR, MR systems can support more direct (manual) interaction of the user with real and/or virtual objects, which is key to achieve active learner participation and skill acquisition (Wang and Dunston, 2005; Pan *et al.*, 2006). However, developments in MR are more recent and still in their infancy, essentially because of the higher technical challenges surrounding specific display devices, motion tracking, and conformal mapping of the virtual and real worlds(Martin *et al.*, 2011).

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217 With regard to construction training, MR systems reported to date mainly focus on equipment operator training, with human-in-the-loop simulators. According to the definitions above, 218 219 these simulators can be considered as AV systems. For example, Keskinen et al. (2000) 220 developed a training simulator for hydraulic elevating platforms that integrates a real elevator 221 platform mounted on 6-DOF Stewart platform with a background display screen for 222 visualization of the virtual environment. Standing on the platform, the operator moves it 223 within the virtual environment using its actual command system and receives feedback 224 stimuli through the display and the Stewart platform.

225 Noticeably, this and other similar AV-type systems are not fully immersive and thus, from a 226 visual perspective, do not provide a full sense of presence. In an attempt to address this 227 limitation, Wang et al. (2004) have proposed an AR-based Operator Training System (AR 228 OTS) for heavy construction equipment operator training. In this system, the user operates a 229 real piece of equipment within a large empty space, and feels that s/he and the piece of 230 equipment are immersed in a virtual world (populated with virtual materials) displayed in AR 231 goggles. However, this system appears to have remained a concept, with no technical 232 progress reported to date.

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To the knowledge of the authors, no work has been reported to date on developing MR systems for the training of construction trades, (e.g. roofing, painting and decorating, bricklaying, scaffolding, etc.). The particularity of those trades is that the trainee must be in direct manual contact with tools and materials. Immersing their work thus requires specific interfaces for tracking the limbs of trainees (particularly the arms and hands), and integratingthe manipulations with virtual environments.

Research has been widely conducted to develop such interfaces. Haptic gloves or other worn devices are investigated (Tzafestas, 2003; Buchmann *et al.*, 2004), but are invasive. Noninvasive vision-based body tracking solutions have also been considered (Hamer *et al.*, 2010), but are usable only within very small spaces. Thus, despite continuous improvements, current solutions for manual interactions with virtual environments do not provide the richness and interactivity required for effective trade training.

In addition, there is a strong argument that MR should not (yet) be used for virtualizing 'manual' tasks; traditional training approaches using real manipulation of real materials and tools must remain the standard. Instead, MR could be solely focused on enabling existing students training in college workshops to develop their skills within challenging realistic site conditions, such as working at height. In other words, MR should be used to immerse both 'trainees and their manual tasks' in varying and challenging virtual environments.

As mentioned earlier, construction site experience is a vital and integral part of apprenticeship training and therefore MR technology could help in preparing trainees for actual site conditions. However, it should be viewed as complementary to real site experience and not a replacement. It could be used as a transition to establish the trainees' readiness before they can actually go on-site.

257 Need Identification, Functional Analysis, and Current System

It was concluded in the previous section that construction trade training can benefit from MR by employing it solely to visually immerse trainees, while they conduct training activities with real tools and materials. Referring to the taxonomy of Milgram *et al.* (1994; 1999), the 261 type of system required appears to correspond to MR systems they classify as *Class 3* or 262 Class 4 (see Table 1). However, we also observe that, from a visualization viewpoint, this 263 more specifically requires that the trainee be able to see their real body and real work (tools, 264 material), and see these immersed within a virtual world. This means that the system would have to calculate in real-time in which parts of the user's field of view the virtual world must 265 266 be overlaid on the real world, and in which parts it should not. In other words, the system needs to deliver AR functionality with (local) occlusion handling, which requires that the 3D 267 268 state of the real world be known accurately and in real-time (the 3D state of the virtual world 269 is naturally already known). Referring again to the taxonomy of Milgram et al. (1994; 1999), 270 the type of system required thus needs to have an *Extent of (Real) World Knowledge (EWK)* 271 where the depth map of the real world from the user's viewpoint is completely modelled (see 272 Figure 3). 273

- Table 1: Some major differences between classes of Mixed Reality (MR) displays:
 reproduced from Milgram *et al.* (1994).
- 276
- Figure 3: Extent of World Knowledge (EWK) dimension;
 reproduced from Milgram *et al.*, (1994).
- 279

From this analysis, we have derived a system's process that includes five specificfunctionalities and corresponding components (Figure 4):

6-DOF head tracker: provides the 3D pose (i.e. location and orientation) of the user's
 head in real-time;

- *Depth sensor*: provides a depth map of the environment in the field of view of the user;
- *Virtual World Simulator / Game Engine*: simulates the virtual 3D environment and is
 used to generated views of it from given locations;
- Processing Unit: uses the information provided by the three components above to
 calculate the user's views of the mixed real and virtual worlds to be displayed in the
 HMD in real-time;
- *HMD* (preferably, but not necessarily, see-through): is used to display the views
 generated by the Processing Unit.

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Figure 4: Process and associated components for delivering the envisioned immersive MR environment.

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In the following, we present our progress to date that involves the implementation of four ofthe five components above:

6-DOF Head Tracker: The 6-DOF head tracking (i.e. localization) is probably the most critical functionality to be delivered by real-time MR systems. Localization is even more critical for MR systems than for VR systems, because poor pose tracking is far more disturbing in MR scenarios since these require the virtual display content to be very accurately aligned with the reality. Robust localization is critical to user experience.

304 Guaranteeing continuous operation while the user is moving is already a challenge; 305 doing it without requiring complex and expensive set-up, is an even greater one. Our 306 main contribution in this paper is an original cost-effective visual-inertial 6-DOF head

307 tracker. The system is detailed in the section below, and its performance is
308 particularly assessed in the experiments reported later on.

- Game Engine: we integrated our 6-DOF Head Tracking system as a third-party component to the Unity 3D game engine (Unity 3D, 2014). This gives our approach a wider applicability and scalability to a range of different training scenarios, thus providing flexibility to different operative trades. Game engines also have the important advantage of already providing optimized capabilities for high-quality rendering and user interaction within complex virtual environments.
- *HMD*: Our system currently employs the Oculus Rift (Oculus, 2013) that is a non-see through HMD, i.e. VR, device that offers great immersive experience with a 110°
 field of view.
- Processing Unit: as discussed below, the Depth Sensing component has not been implemented yet. As a result, our current system can only deliver VR functionality, not AR. Therefore, the Processing Unit is currently only partially implemented, as it only calculates views of the virtual 3D environment (managed by the Game Engine)
 to be displayed on the HMD.

At this stage, we have not implemented any solution for the Depth Sensing component. However, a solution is proposed in the *Future Work* section at the end of this paper. Similarly, our envisioned system needs to deliver AR, not just VR functionality. Our proposed approach to achieve this is also discussed in the *Future Work* section.

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328 As mentioned above, out of the four components implemented to date, the 6-DOF Head 329 Tracking component is the most challenging. The approach we developed is a significant 330 computational contribution, and this paper thus particularly focuses on presenting it and 331 assessing its performance. The following section presents the approach.

332 6-DOF Head Tracker

This section is divided in two sub-sections. The first sub-section provides a short review of prior works on localization methods, identifying their strengths and weaknesses. The second sub-section presents our visual-inertial approach.

336 Introduction

337 Numerous absolute position tracking technologies exist, but some either do not work indoor 338 (e.g. GNSS; e.g. see the work of Kamat et al. (Talmaki and Kamat, 2014)) or do not provide 339 the level of accuracy necessary for MR applications (e.g. UWB, RFID, Video, depth sensors) 340 (Teizer and Vela, 2009; Gong and Caldas, 2009; Cheng et al, 2011; Yang et al., 2011; 341 Escorcia et al., 2012; Ray and Teizer, 2012; Teizer et al., 2013). In construction, Vision-342 based approaches with multiple tracked markers, such as commonly considered Infrared-Red 343 vision-based systems, can provide accurate 6-DOF data, but require significant infrastructure 344 (cost), line-of-sight, and are somewhat invasive. Inertial Measurement Units (IMU), that 345 integrate numerous sensors like gyroscopes, accelerometers, compass, gravity sensor, and 346 magnetometer, are mainly used to track orientation. Although IMUs can theoretically also be 347 used to track translation, our experience (see Section Experimental Results), as well as that of 348 others (e.g. see (Borenstein et al., 2009)), is that this is prone to rapid divergence, hence 349 unreliable information.

In an effort to address these limitations, we have been investigating an alternative visualinertial approach for 6-DOF position tracking that integrates an IMU and a markerless visionbased system. Visual-inertial *ego-motion* approaches have been conceived in general to represent an affordable technology, also usually requiring limited set-up. Complementary action of visual and inertial data can increase robustness and accuracy in determining both position and orientation even in response to faster motion (Welch and Foxlin 2002, Bleser
and Stricker 2008). Our specific approach, detailed in the following section, has been
designed to handle system outages and deliver continued tracking at the required quality.

358 Our Approach

The proposed head tracking system relies on the complementary action of visual and inertial tracking. We have conceived an *ego-motion (or inside-out)* localization approach, which integrates visual data of the surrounding environment (training room), acquired by a monocular camera mounted integral with the HMD *Oculus Rift* (we use the first version), together with inertial data provided by the IMU embedded into the HMD *Oculus Rift*. A dedicated computing framework robustly integrates this information, providing in real-time a stable estimation of the position and the orientation of the trainee's head.

366 As far as the visual approach is concerned, it provides *global references* that can be used for 367 localizing from scratch the trainee's head within the training room, also recovering its pose in 368 case of system outage. Following the general markerless vision-based approach proposed in (Carozza et al., 2014a), the method proposed here puts in place new computational strategies 369 370 in order to increase the robustness (e.g., for fast motion) and the responsiveness of the 371 system. Indeed, in order to deliver a consistent user experience, system outages, as well as 372 drift and jitter effects, must be minimized for general motion patterns. The proposed method 373 follows two main stages, i.e. an off-line reconstruction stage and on-line localization stage, 374 as outlined in Figure 5.

375 Off-line Reconstruction Stage

The *off-line reconstruction stage* (Figure 5 left) is performed in advance, once and for all, by automatically processing pictures of the training room, acquired by the camera from different viewpoints, according to the Structure from Motion *Bundler* framework (Snavely 2008). The
training room has been textured in advance by using posters (Figure 5 (a)) – with a random
layout – so that a *3D map of visual references* can be reliably reconstructed (Figure 5 (b)).
The reconstructed point cloud is then used as reference for the alignment of the virtual
training scenario with the (real) world reference frame (Figure 5 (c)).

A multi-feature framework has been developed so that it is possible to associate different *visual descriptors*, with flexible performance in terms of robustness and time processing, to the reconstructed 3D point cloud. Based on the recent comparative evaluation of visual features' performance (Gauglitz 2011), SURF (Bay *et al.* 2008) and BRISK (Leutenegger *et al.* 2011) descriptors have been evaluated.

388 The result of the process above is a database of repeatable visual descriptors, referred in the 389 3D space, or world reference frame (WRF), and that is used for the subsequent on-line 390 localization stage.

391 On-line Localization Stage

392 At the beginning of *on-line* operations, visual features extracted from the images acquired by 393 the camera mounted on the HMD (Figure 5 (d)) are robustly and efficiently matched with the 394 visual features stored in the map, so that the *global pose* of the camera can be estimated from the resulting 2D/3D correspondences (Figure 5 (e), left) by means of *camera resectioning* 395 396 (Hartley and Zissermann, 2003). In particular, for each frame the set of query descriptors is 397 matched through *fast approximate nearest neighbour* search over the whole room map, and 398 the 3-point algorithm (Haralick, 1994) is applied on the set of inliers resulting from a robust 399 RANSAC (Fischler and Bolles, 1981) filtering stage. In this way, the system is *initialized* to 400 its starting absolute pose $P_{WRF}^- = (p_{WRF}, R_{WRF})$, where p_{WRF} and R_{WRF} are respectively the 401 position vector and the orientation matrix with respect to the WRF.

402 However, the global matching approach can be (a) not sufficiently precise and robust, due to 403 image degradation during fast movements, or (b) not sufficiently efficient for real-time 404 performance (due to query search overhead over the whole database). Accordingly, a *feature* 405 tracking strategy is used together with the IMU data for the subsequent frames. A frame-to-406 frame tracking approach based on the Kanade-Lucas-Tomasi (KLT) tracker (Shi and Tomasi 407 1994) is employed between consecutive frames, with the advantage of being very efficient 408 and exploiting spatio-temporal contiguity to track faster motions. More details about the 409 feature tracking approach, and in particular *tracker reinitialization* to allow tracking over 410 long periods, can be found in (Carozza et al., 2013). Note that a pin-hole camera model is 411 considered throughout all the stages of the vision-based approach, taking into account also 412 lens radial distortion.

413 Inertial data are used jointly with the visual data in an Extended Kalman Filter (EKF) 414 framework (Figure 5 (e)). This framework is necessary to filter the noise affecting both 415 information sources and provide a more stable and smoother head trajectory. A *loosely*-416 *coupled sensor fusion* approach has been implemented, which initially processes *separately* 417 inertial and visual data to achieve a robust estimate of the *orientation* and a set of visual 418 inliers. Then, this information is fused together into the EKF to estimate the position. The 419 measurement equations used in the EKF involve the visual 2D/3D correspondences 420 according to the camera (non-linear) projective transformation, $\Pi(P_{WRF})$, related to the predicted pose $P_{WRF}^- = (p_{WRF}, R_{WRF})$, by computing the predicted projections m^- of the 3D 421 422 points X onto the image plane:

$$m^- = \Pi(P^-_{WRF})X$$

The *loosely-coupled approach* has the advantage of decoupling position and orientation noises, so that the system is inherently more immune to pose divergence possibly rising from non-linearities inherent in the projective model. 426 However, in order to be fused consistently with the visual data, the inertial data must be 427 referred to the same absolute reference frame of the visual data (i.e. the training room). We 428 developed an on-the-fly camera-IMU calibration routine, which automatically processes the 429 first N_{calib} pairs of visual and inertial data following the very first successful initialization to 430 estimate the *calibration matrix* relating the inertial reference frame to the global reference 431 frame. Our calibration method is similar to the classic hand-eye calibration (see Lobo et al. 432 2007), but it can be employed on-line since the relative translation between the camera and 433 the IMU centres does not need to be estimated (it is not taken into account into the 434 subsequent calculations).

It is worth noting that the IMU measures represent the only data available in case of outage of the visual approach, due to image degradation, poor texturing, or occlusion, for example. In these cases, our method relies on the sole orientation information measured by the IMU (*Tracking_IMU*), while data measured from the accelerometers are not directly employed to estimate position, which would rapidly result in positional drift. Among the different approaches applicable in this situation, we have decided to assume the position fixed and invoke frequently a *relocalization* routine.

442 During the *relocalization* stage, the matching approach employed for *initialization* is applied 443 on the map points only within an expanded camera frustum, computed from the last 444 successfully computed pose. This guided search has the advantage of being significantly 445 faster. If the *relocalization* fails, the system enters the *Tracking_IMU* state for N_{lost} 446 consecutive relocalization attempts at maximum, then invoking the *inizialization*.

In Figure 6, the state diagram of the adopted 6-DOF tracking framework summarizes the main transitions occurring during on-line operations among the different stages encountered above. These transitions illustrate at a high level the continued operation of the system over

450	long periods from the initialization to the response and recovery from different system
451	outages.
452	
453	Figure 5: An overview of the main components of our proposed approach to 6-DOF head tracking and HMD-
454	based immersion.
455	
456	Figure 6: State diagram of the visual inertial 6-DOF tracking framework. "1" and "0" represent successful or
457	unsuccessful state execution, respectively.
458	
459	Finally, for each frame, once the head pose is estimated, any 3D graphic model/virtual
460	environment can be rendered consistently with the estimated viewpoint. For example, Figure
461	5 (f) shows the rendered views of a virtual model of the training room corresponding to the
462	head locations estimated using the two head-mounted camera views shown in Figure 5 (d).
463	
464	We acknowledge that vision-based location systems have the limitation of requiring line-of-
465	sight to sufficiently textured surfaces. However, our system is targeted towards controlled
466	environments for which the surrounding boundary walls can be appropriately textured as
467	needed. Furthermore, the inertial system increases the robustness of the system by taking
468	over orientation tracking upon failure of the vision-based system (that is reinitialized as
469	frequently as possible).

470 **Experimental Results**

In this section, we first report results on the performance of our 6-DOF head tracking system. This is then followed by results from our current full system in action, that integrates our head tracking system with a VR Immersive Environment that uses the Unity game engine to manage the virtual 3D model (game environment / simulation) and generate the views of it in real-time, and the *Oculus Rift* to display these views.

All the experiments were performed in a rectangular room of size 3.75 m x 5.70 m with walls covered with posters arranged according to a random layout. Note, however, that these experiments are only part of a series of experiments that have been conducted in different rooms with varying poster arrangements and geometrical structures, that have shown no substantial difference in performance (e.g. see (Carozza *et al.*, 2013)).

481 Head Tracking

482 Our proposed 6-DOF head tracking approach has been tested on several different live
483 sequences, showing real-time performance (30 fps on the average on a Dell Alienware
484 Aurora PC) and an overall good robustness to user movements, as detailed below.

485 The off-line reconstruction process has led to a *map* of 3,277 SURF and 2,675 BRISK
486 descriptors, respectively, which present different spatial accuracy and distribution.

To assess localization performance, a virtual model of the room has been reconstructed by remeshing a laser-scan acquisition of the room and aligning this mesh with the 3D feature database. This virtual model enables the rendering of the view of the room for each computed location, which can then be visually compared with the real view of the room from the camera image to assess localization performance (Figure 5, left, third row).

492 In Table 2 we present the statistics related to the on-line performance for a looping path 493 sequence of 2 minutes (3,600 frames) for BRISK and SURF features, respectively (shown in 494 Figure 7). The sequence contains significant motion patterns (e.g. rapid head shaking and 495 bending) to assess the robustness of the method while the user is free to move. The table lists, for the two different types of visual features, the number of frames (#FLoc) successfully 496 497 localized by the visual-inertial sensor fusion approach as well as the number of frames 498 (#F_{IMU}) for which the visual information is deemed unreliable (e.g. due to fast motion blur, 499 occlusion, poor texturing) and the IMU information only is used (*Tracking IMU*). The table 500 also provides the computational times achieved for visual matching (i.e. initialization and 501 *relocalization*) (T_M), and visual-inertial tracking (T_T). As it can be seen, the BRISK approach 502 provides in general better resilience to visual outages, also because of its better computational 503 performance (T_M) during visual matching (third column of Table 2).

504

505Table 2: Statistics related to the on-line performance for a looping path sequence of 2 minutes (3,600 frames),506using either BRISK or SURF features. The table lists the number of frames localized by the sensor fusion507approach ($\#F_{Loc}$), and in the TRACKING_IMU mode ($\#F_{IMU}$), together with related timings (in ms,508mean±std.dev.) for visual matching (T_M) and visual-inertial tracking (T_T).

509

510 Figure 7: Trajectories (top view) estimated by the head tracking method for BRISK and SURF.

511

512 The different performance for the BRISK and SURF methods is also the result of the 513 different frequency of *relocalization* following tracking failure. Indeed, because SURF 514 matching is slower (Table 2, third column), *relocalization* using SURF cannot be invoked too 515 often, when compared to BRISK, in order not to impact time performance (and so minimize 516 latency). As a result, with SURF, the system is exposed to longer periods of lack of positional
517 information (remaining in the *Tracking_IMU* mode), leading potentially to positional drift.

518

519 In Figure 8 the views of the virtual model of the room, rendered according to the estimated 520 viewpoints, are shown for both methods (second and third columns) together with the real 521 images (i.e. ground truth) acquired by the head-mounted camera (first column) for two 522 significant sample time instants. It can be seen that, even in the presence of image 523 degradation due to fast movements, the real and the virtual views generally appear in good 524 visual agreement. However, as expected from the considerations above, the BRISK approach 525 shows a better robustness and limited long-term drift. Furthermore, being a looping path 526 sequence, the corresponding 3D loop closure error (the measured distance between the initial 527 and final position) can be used as a measure of the drift effect. It has been estimated to be 0.09 m for the BRISK method, and 0.13 m for the SURF method. A longer four-minute 528 529 sequence, with the user free to walk but returning three times to the same predefined location, 530 has shown an average error of 0.18 m for BRISK and 0.88 m for SURF. That second 531 sequence presents challenging motion patterns similar to the ones encountered in the first 532 sequence, showing a similar behaviour for recovering after system outages and reinitializing 533 the system. Further results confirming the robustness of the system during continued 534 operation, particularly when using BRISK features, can also be found in (Carozza et al., 535 2014b) and (Carozza et al., 2014c).

536

Figure 8: Comparison between real images acquired live by the camera (after lens distortion compensation) - at
first row: frame #525, second row: frame #1368 - and views of the virtual training room model rendered
according to the viewpoint estimated using BRISK and SURF features, for fast motion.

540

These experimental results show good promise. However, the complete validation of the head tracking system will only be achieved once it will be integrated within an AR display system, which will enable the much more clear identification of drift and other pose estimation errors, and their actual impact on the overall system's usability.

545 Application: Experiencing Height

We were able to already employ our overall VR system to enable construction trainees to experience height. As mentioned earlier, for H&S reasons trainees in colleges cannot be physically put at heights above approx. 8m, so that many trainees may not have experienced common work-at-height situations prior to their first day on the job, and hence do not really know how well they can cope. Two scenarios have been considered: standing and moving on a scaffold at 10m height, and sitting on a structural steel beam at 100m height. Figure 9 illustrates users immersed in the two scenarios.

553

Figure 9: Application of the localization approach to two virtual scenarios: (a) standing and moving on a 10m
scaffold; (b) sitting on a beam at 100m height (virtual model of the city courtesy of ESRI).

556

Early presentation of the system to FE college students and trainers received positive feedback, confirming that such a system could play a role in enabling trainees to safely experience different working conditions at height, to develop their readiness to such situations that they may later encounter in the real construction project environment.

561

562 Yet, it is interesting to discuss issues surrounding motion sickness. Indeed, users of VR 563 goggles like Oculus have expressed concerns regarding motion sickness even after short 564 utilisation (although it has also been reported that this sickness can disappear after some 565 adaptation time). However, we note that those sicknesses appear to be reported in the case of current gaming scenarios where the user remains seated the whole time, in which case the 566 567 visualized body motion does not match the actual motion felt through other body senses. As 568 shown in previous studies (Laviola, 2000; Stanney, 2002; Chen et al, 2013), we believe that 569 an additional advantage of 6-DOF motion head tracking systems like the one proposed here is 570 that the visualized body motion directly and consistently relates to actual body motion, which 571 should reduce the risk of motion sickness.

572 Conclusion and Future Work

573 The construction industry has traditionally shown poor levels of investment in R&D and 574 innovation and as such is slow in the uptake of new technologies, in particular when it comes 575 to the application of new technologies for education and training (CIOB, 2007). It is claimed 576 that "courses do not prepare students for the realities of construction sites or even the basics 577 of health and safety and there is a bias towards the traditional trades and sketchy provision 578 for new technologies" (Knutt, 2012). This underlines the need for investment in new 579 technologies to support construction training. If colleges want to become part of future 580 education they should create change rather than waiting for it to happen to them (Hilpern, 581 2007).

582

583 The system presented in this paper is a novel approach that has the potential to transform 584 construction trade training. The current VR Immersive Environment enables trainees to experience height, without involving any actual work. This simple exposure already enables trainees to experience such heights and assess their comfort in standing and eventually working in such conditions. Ultimately, it could even enable them to start accustom themselves to such conditions.

589 From a technical viewpoint, the main contribution of this paper is the presentation of an 590 original visual-inertial 6-DOF head tracking system whose performance is shown to be 591 promising.

It is worth noting that the choice of the system components – making use of commodity hardware and requiring very limited set-up (e.g. no installation and calibration of markers and multiple camera systems) – as well as the computing strategies adopted for each system stage already make our current VR system a valid alternative to existing immersive systems, such as CAVE (Cruz-Neira *et al.*, 1992).

597

598 The next phase of our technical work will aim to complete the development of the envisioned 599 MR immersive environment where the trainee can experience site conditions whilst 600 performing real tasks. The accrued benefits of the application of MR and motion tracking 601 technologies can include: enhancing the experience of apprenticeship training, 602 complementing industrial placement and establishing site readiness, skills transfer and 603 enhancement, performance measurement, benchmarking and recording, low operational cost 604 and transferability across the industry. However, all these claims will require further research 605 for validation using actual data.

From a technical viewpoint, our next step is to develop the depth sensing component and review the world mixing component, so that trainees can see their own body and selected parts of the surrounding real world, which is necessary to enable them to conduct actual

609 construction tasks within varying virtual environments. For depth sensing, we propose to 610 integrate a 3D camera (e.g. SoftKinetic DepthSense 325 that provides range sensing up to 611 1.5m (SoftKinetic, 2013)), on top of the HMD and use the depth information to calculate in 612 real-time the parts of the views of the virtual 3D environments that should be displayed on 613 top of the real view, and those that should not be shown (i.e. the parts of the user's view 614 where s/he should still be able to view the real world). For the AR viewing functionality (i.e. 615 AR HMD), two approaches are possible. The first is to attach two cameras to the HMD and 616 use the real-time imagery provided by these to create the mixed reality views, as recently demonstrated by Steptoe et al. (Steptoe, 2014). Alternatively, see-through HMDs, i.e. AR 617 618 HMDs, can be employed that prevent altogether the need to acquire, process and consistently 619 display views of the real world. In our system, we propose to use of the META Spaceglasses 620 (META, 2013), a device that will be available in 2014. It is interesting to note that the META 621 Spaceglasses, just like the Oculus Rift, integrate a high-frequency IMU (see discussion in the 622 following bullet). But, even more interesting is the fact that the *Spaceglasses* also integrate a 623 DepthSense 325 camera. The Spaceglasses thus seem to already deliver many of the 624 functionalities required by our envisioned system.

625

Finally, from an application viewpoint, it would be interesting to conduct a comparative study between traditional forms of construction training delivery and assessment (in a conventional workshop or classroom setting) as opposed to when using MR in order to demonstrate the impact of employing such technologies on trainees' performance.

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