

Embedded Augmented Reality Training System for Dynamic Human-Robot Cooperation

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ABSTRACT

In industrial production of high-wage countries, advanced automation technologies can partially compensate the lack of skilled workers, but human effectiveness and flexibility is still essential in many scenarios. Implementing the idea of mutual completion, direct human-robot cooperation appears suitable where strong forces are needed but human flexibility is indispensable. For this, the explicit spatial separation between robot and worker has to be given up. Prior to installation of sophisticated monitoring systems on the shop floor, advanced simulation methodologies have to be embedded directly into the production cell to design such cooperation scenarios safe and effective likewise. An immersive simulation system is presented which allows an optical see-through augmented reality (AR) configuration where the user is able to perceive the real tool in his hand. Alternatively, the system also supports a pure virtual reality (VR) mode where all objects' visualization is artificial. Both variants accord in direct confrontation with a virtual robot and real-time physics simulation capabilities. A usability study with 40 subjects has been conducted, featuring robotically supported cast part blasting as experimental task. Results of user performance focussing on executing times and shooting accuracy indicate a tie between AR and VR and a surpassing overall usability in both configurations, but the users' personal preference trends towards AR.

1.0 INTRODUCTION

Due to demographic changes in high-wage countries, a significant lack of manufacturing specialists and skilled workers is foreseeable. Furthermore, constantly increasing pressure on costs, quality and timing combined with short product lifecycles and diversified product variants tightens selling conditions. Consequently, new manufacturing methods and appropriate simulation techniques are needed in order to strengthen competitiveness. Heavyweight goods handling in small-lot production is a good example where robots could ideally support human workers. This approach is particularly interesting for small and medium-sized enterprises, as demonstrated in the SMERobot initiative [1]. The sticking point is that the spatial separation between human and robot defined in international industrial norms like ISO 10218 [2] has to be given up. Therefore, besides safeguarding monitoring systems installed on the shop floor [3], new immersive simulation techniques are needed to minimize the risk of injury prior to start of production. Embedding the user directly into the virtual scene, advanced immersion could facilitate and accelerate safety assessments. Consequently, research efforts at the Institute of Industrial Engineering and Ergonomics at RWTH Aachen University feature advanced virtual and augmented reality technologies for more immediateness and realism.

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2.0 VIRTUAL TECHNOLOGIES IN PROCESS SIMULATION AND ROBOTICS

Desktop-PC-based 3D simulation environments are state of the art nowadays and cover most scenarios for industrial robotics in various use cases: from heavyweight goods handling to spot welding and spray painting, robots, fixtures and most equipment can be modelled and simulated [4]. This allows building up complete production lines including all challenges which come about like power-up phases, mutual interlocks, dynamic material allocation etc. Nevertheless, human workers in general and highly skilled workers in particular are still rarely taken into account. Representation with digital human models offers advanced analysis capabilities in terms of proportions, stress analysis, field of view etc. [5], but due to their high number of degrees of freedom, digital human models are cumbersome to handle, especially in interactive real-time scenarios.

AR and VR allow direct (egocentric) confrontation of the user with the virtual objects. Humanoid robot interaction is a well-know area of application [6]. Robot manufacturers like ABB and KUKA [7] as well as third party researchers [8] have already caught up this track to support and to facilitate robot programming. In this context, an ongoing German research project with participation from industry as well as research labs called AVILUS focuses on further improvement of virtual and augmented reality technologies in product development and service [9]. Still, support for direct human-robot cooperation in terms of manufacturing is rarely featured.

For AR, which is generally in regard to technology more challenging than VR for convincing results, desktop monitors with live video stream or images are most often used. Optical see-through (OST) head-mounted displays (HMDs) still lack in usability and ergonomics because of their size, weight, resolution, and the hard-to-realize occlusion of real behind virtual objects. Nevertheless, they offer deep immersion and require less space and financial effort in comparison to more elaborate alternatives like CAVE systems, for example. Current developments concentrate on advanced visual combination of virtual and real objects with addressable focal planes [10], for example. Accurate and easy-to-use calibration routines for OST HMDs remains a challenging task; established methods are based on matching of virtual over real objects [11], newer approaches use cameras looking directly through the HMD optics to exploit both the intrinsic and extrinsic parameters [12].

3.0 INDUSTRIAL USE CASE

Industrial casting of massive metallic parts like crank cases is accompanied by undesirable disposition of sand relics. Cleaning is usually done through abrasive blasting with water, dissolvers or carbon dioxide pellets. The last-mentioned alternative is most recommendable since carbon dioxide is electrically insulating, chemically inert, nontoxic and inflammable [13]. Well-directed laboring is highly advisable for surface protection and economic pellet exhaustion. Typically, the pellets are shot salvo-wise with a specialized high-pressure pistol.

In mass production, the cast parts are handled by highly-automated conveyor systems for fast processing. In small-lot production, however, operators depend on mobile handling devices like cranes and jack-up platforms. Frequent usage of these is cumbersome and dangerous through perpetual hooking and unhooking, clamping and unclamping etc. Direct human-robot cooperation can bring about a significant advantage through the idea of mutual completion: here, the robot could indefatigably cover flexible part handling (see figure 1) while the human worker could concentrate on part inspection and relics removal. An adequate simulation environment needs to account for realistic depth perception as well as lifelike appearance of the robot, the tool in the user's hand and the abrasive medium exhausted by the tool. Consequently, visual as well as haptic and auditory perception are important factors for immersion and a realistic overall impression.



Figure 1: Heavyweight goods handling with a robot (left, source: Duerr Ecoclean [14]) and worker with equipment for abrasive carbon pellet blasting (right, source: Reglotec [15])

4.0 DESIGN OF THE AUGMENTED REALITY TRAINING SYSTEM

4.1 Hardware

A stereoscopic high-resolution 24 bit colour HMD *nVisor ST* by NVIS is used, with a 60 degrees diagonal field of view (FOV) for each eye and an optional 40% see-through light transmission. The HMD is fastened on a carrier which reduces physical stress on the user's head and neck. For empirical studies, this fixation also guarantees the same perspective for all subjects, independently from the size of the upper part of the body. Hence, the user is sitting on a hydraulically height-adjustable seat (see figure 2).

A simplified model of a real blasting pistol has been designed in a CAD environment and then hand-crafted from aluminium and coated with non-reflective adhesive foil. The pistol's trigger is conjoined with the left button of an integrated computer mouse. The mouse wheel and the right mouse button are still accessible with the thumb and can be allocated with arbitrary functionalities. Both the display and the pistol are fitted out with infrared light reflective marker targets so that their transformation (translation and rotation) is tracked by an optical tracking system by A.R.T. It consists of four *ARTtrack2* infrared cameras, each processing sixty frames per second and together covering a working volume of about thirty-two cubic-meters. This allows accuracy in sub-millimeter range, depending on the size of the targets.

Data processing and graphical rendering is done by a standard Intel Core2 Duo CPU system with 3.0 Gigahertz and 3 Gigabytes of RAM plus a *GeForce 9800 GX2* graphics accelerator by Asus. It includes a dual GPU architecture and directly supports hardware-accelerated real-time physics simulation. Each of its two DVI ports directly feeds one of the HMD's input ports.

4.2 Software

While the hardware is mainly a composition of high quality off-the-shelf components, the software is self-developed in C++, based on OpenGL and specialized libraries for physics simulation and sound, focusing on tool-based manufacturing scenarios. Optical See-Through Augmented Reality (AR) and pure Virtual Reality (VR) are supported. While AR allows direct combination of the real pistol and virtual objects and so is actually closer to reality, it requires proper calibration and can lead to optical irritations, e. g. by frequent change of near and far accommodation. Additionally, all virtual geometries appear semi-

transparent. VR offers a more homogenous and consistent overall impression with opaque geometry visualization including pistol rendering. However, latency effects may impede hand-eye coordination (see figure 2).

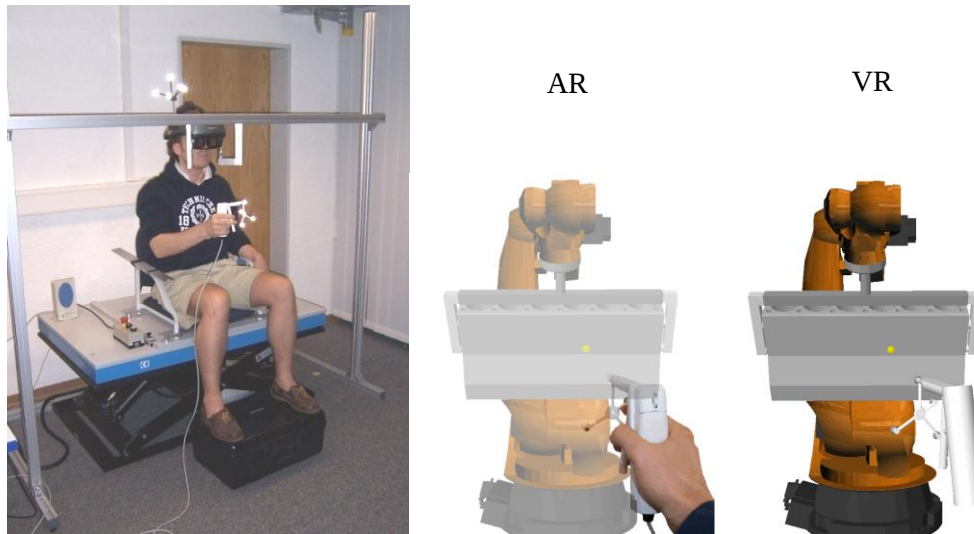


Figure 2: The developed apparatus (left) and the two visualization modes AR (middle) and VR (left) with a yellow sand relic on the part as target

Stereoscopy is an important factor for depth perception in virtual worlds. Depending on the eye distance and the focused distance (convergence angle), a different image for each eye is generated separately for binocularity. The virtual camera's field of view is adjusted to the HDM's field of view to render realistic proportions. Especially for optical see-through AR, proper calibration is important to match real and virtual objects. In this case, the virtual pellets must leave the real barrel's muzzle as closely as possible. Hence, a calibration procedure derived from the fast and widely recommended "Stylus-Mark Calibration" method [16] has been implemented where the real and the virtual pistol simply need to get overlapped manually at specific spatial positions.

As for the supported geometry file formats, besides X3D (XML-compliant successor of VRML by the Web3D organization [17]), the industry-widespread JT (Jupiter Tessellation) format, propagated by the JT Open Community [18], is featured for more industrial relevance. In this study, a detailed model of KUKA's mid-weight handling robot KR180 has been used. The robot's grippers as well as the simplified cast part (six cylinder crank case) have been designed in CAD.

Surface effects like reflections and bumps make virtual objects look more realistic. In depth buffer based rendering, fragment and vertex shaders allow this very efficiently, as described by Rost [19]. Executed directly on the GPU, they allow dynamic light effects in real-time without the need to modify the source geometry file. An environment map shader is used here to give the virtual robot a reflective look and a procedural shader is used for the base plate's regular surface for much smoother renderings in comparison to standard textures.

In the real world, gravitation is responsible for material falling down and ballistic trajectories of accelerated masses. Since this has significant impact on the credibility of any environment (real or artificial), the popular real-time physics engine *PhysX* by NVIDIA [20] has been integrated. The calculations are deterministic for constant time step sizes, but it must be pointed out the numerical

equation solver compromises with speed and accuracy to achieve real-time capabilities on standard hardware. As sound has a significant impact on immersion, the FMOD sound engine by Firelight Technologies [21] has been implemented to allow synthesized generation of robotic movements and blasting sounds as acoustic feedback for the user.

For the robot's movements, the joints' postures can be controlled via a process server which comprises a mathematical model of the robot (industrial robotic arm with six axes). Forward kinematics are modeled based on standard Denavit-Hartenberg's terminology [22], inverse kinematics are calculated with a Taylor expansion approach. Once the server is engaged to play a process sequence like pick-and-place, it broadcasts all pre-calculated robotic status information to the graphics client via UDP Ethernet protocol. For conferencing scenarios, multiple graphics clients are supported. In more interactive use cases with just one graphics client, the joint angles can also be interpolated in real-time directly on the client side, given that all target joint angles are known. As the collaboration of worker and robot needs to be highly dynamic for an optimized workflow, the infrared tracking system tracing all pistol movements is used at the same time as supervision system. In doing so, the system makes sure that the robot only moves when the workers hands are in a predefined safety zone. Accordingly, a virtual signal light in the user's FOV continuously notifies about the robot's system state: to take down the pistol into the safety area for the robot to start moving (red light), to keep the pistol within the safety while the robot is moving (yellow light) or to raise the pistol to start working on the part (green light).

5.0 EMPIRICAL USABILITY STUDY

On the shop floor, the clearance between worker and robot is most significant for safety and efficiency. Consequently, the variant (AR or VR) with the most realistic synthesis of depth, proportions, dynamics and usability should be favored. An empirical usability study with 40 subjects (20 male and 20 female) has been conducted to compare user performance and workload in both system variants.

5.1 Experimental Design

The experimental design consists of a pre-phase, a main experimental phase and a post-phase. In the pre-phase, a general questionnaire on education and experiences has been carried out. Besides the age and educational background, the emphasis here was to find out about pre-experiences with 3D applications like CAD tools and 3D games like ego shooters. 22 of the 40 subjects had at least casual experiences either with 3D applications or 3D computer games. A test on visual acuity (including stereopsis and color-blindness) granted a minimum level of acuity of 80% with both eyes. Schuhfried's Vienna Test System motor activity test [23] ensured a "error-time/overall-time" ratio of below 0.5 for the steadiness test and line following test.

The main experimental phase was split into two sub-phases where the participants worked with the AR and VR configuration of the system one after the other, order randomized. In each configuration, 20 relics had to get hit off the virtual cast part. The relics' sizes were uniformly distributed between 10mm and 40mm and they were randomly placed on either of five sides of the part: on the front, left, right, top or bottom side. Depending on the side, the robot engaged one of five different postures, presenting the concerning side directly to the user for ideal treatment. During robot movement time (constantly 2.0 seconds), the user had to keep the pistol in a defined 2x2x2 m³ cube safety area space located at the end of the chair's arm rest. In doing so, a common start position for all shooting actions was determined likewise.

Each subject was directly confronted with a virtual robot visualized in the height-fixated HMD. A signal light in the user's field of view indicated the robot's current state. As shown in the state chart in figure 3 on the next page, three robot states were possible:

- (I) When there were still relics to remove and the robot tried to get into the next posture (randomly generated) but could not because the user's pistol was not within the safety area, the robot halted (red light).
- (II) As soon as the user entered the safety area, the robot began to move (yellow light). If the user left the safety area unless the robot had reached the next posture, the robot halted again (red light).
- (III) Having reached the next posture, a new relic was instantly generated on the part. The execution time was tracked, as well as the number of pellets the user needs to hit the relic. Both numbers were permanently visible in the user's field of view for motivation and control. As soon as the relic was hit, the user had to re-enter the pistol into the safety area for the next loop until 20 relics had been hit.

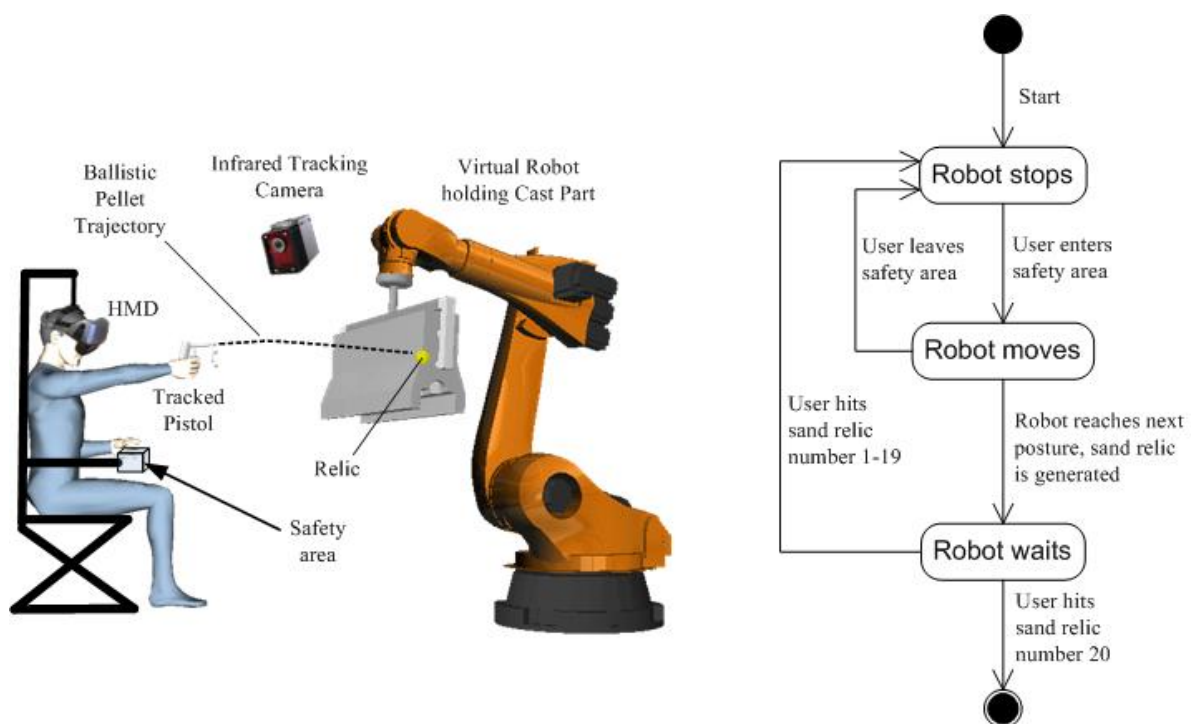


Figure 3: Schematic illustration of experimental setup (left) and virtual robot state chart (right)

Since all 40 subjects worked in both variants and removed 20 relics in each, 800 input/output datasets have been collected for AR as well as VR.

The experiment's closure scheduled the NASA-TLX questionnaire, a multi-dimensional rating procedure based on different subscales including mental demands, physical demands, temporal demands, own performance, effort and frustration. For each subject, the NASA-TLX referred to the last configuration executed only, so either AR or VR. Finally, the personal preference for one variant for regular usage was recorded. All in all, the experiment took less than 45 minutes per subject.

5.2 Independent Variables

The two independent variables that varied uniformly distributed in each configuration were the position of each relic (given by the robot's posture and the position on the part's surface) and the size of the relic on the cast part:

- (a) The position of the relics was uniformly distributed on either side of the part, held by a virtual robot located in 2.5 meters of (virtual) distance from the HMD. Due to robot's poses, the average distance between user and part was 2.1 meters.
- (b) The yellow sphere-shaped sand relics had a uniformly distributed radius between 10mm and 40mm.

5.3 Dependent Variables

The two dependent variables which were tracked per target were the execution time and the number of pellets:

- (a) The execution time in milliseconds was recorded continuously.
- (b) The number of pellets needed to hit a single relic was counted for each target.

5.4 Subjects

The characteristics of the subject group were the following:

- 20 male subjects
- 20 female subjects
- All subjects 19-35 years of age
- All subjects' acuity at least 80% (with both eyes)
- All subjects' motor activity test results with "error-time/overall-time" ratio below 0.5
- All subjects with higher educational background: technicians, students or graduates
- Subjects both experienced (22 of 40) and inexperienced (18 of 40) with 3D applications

5.5 Constraints

Some constraints had to be imposed to decouple the independent variables and to increase the expressiveness of the results:

- The HMD was fixed to 1.5 meters height for standardized perspective for all subjects
- All subjects had to raise pistol up into field of view to avoid shooting "from the hip"
- Pulling trigger resulted in one single virtual pellet shot, no salvo-shooting possible
- Virtual pellets big-sized, light-weight and low-accelerated:
 - Radius: 8mm (→ Volume: 2145mm³)
 - Density: 10 kg/m³ (→ Mass: 0.02145g)
 - Muzzle velocity: 20 m/s

- Gravity was set to 9.81 m/s²
- No air friction simulated

6.0 PREDICTIVE MODEL

An established model to predict execution time T required to rapidly move to a target area is expressed by Fitts' law [24]. Originally, this law is used to model the act of pointing, either by physically touching an object with a hand or finger, or virtually, by pointing to an object on a computer display using a pointing device. Mathematically, Fitts' law has been formulated in several different ways. One well-proven is the "Shannon" formulation:

$$T = a + b \cdot \log_2 \left(1 + \frac{D}{W} \right) \quad (1)$$

The logarithmic expression in (1) is called the "Index of Difficulty" (short: ID) and comprises the distance D and the size W of the target. The constants a and b are task-specific and need to be determined empirically. Obviously, Fitts' law describes a linear relationship between the ID and the time needed to hit a target. As basis for evaluation of 3D stereo displays [25], it has also already shown to be generally applicable for pointing tasks in 3D environments [26] as well. Additionally, it has been utilized for determination of pistol shooting accuracy [27]. The presented experiment is a combination of the two latter: a pistol shooting task in a 3D environment where the distance consists of the way the pistol is moved plus the ballistic trajectory of the pellet when shot. In consequence, the visual feedback is not continuous. Further unique features here in contrast to existing studies are the use of a stereoscopic, height-fixated HMD and the direct comparison of AR and VR. Regression analysis was supposed to bring about scientifically founded adaptability of (1) for this case.

7.0 RESULTS AND DISCUSSION

7.1 Means and Standard Deviations

As expected, the radius of the relics was about 25mm in average (see table 1). The range of relic sizes (from 10mm to 40mm) turned out to be adequate (large sizes for easy aiming, small sizes for hard-to-hit cases). Differences in distance (average: ~2100mm) were a result of the individual height of the seat of a subject, the different postures of the robot and the different positions of the relics on the cast part.

	Augmented Reality		Virtual Reality	
	Mean	Std. Dev.	Mean	Std. Dev.
Relic Size [mm]	26.22	1.8	26.03	1.6
Distance to Relic [mm]	2098.5	66.99	2131.36	67.58

Table 1: Means and standard deviations of independent variables (the size of the relics and their distance from the start position of the pistol) under both experimental conditions, AR and VR

The subjects hit not significantly faster in VR than in AR. However, the dependent t-test shows with $t(40) = 3.05$ ($p < 0.05$) and an effect size of $r = 0.44$ that the number of pellets needed in AR is significantly higher to achieve the same performance: The subjects need 17% more pellets in AR for a

comparable temporal rating (see table 2). An explanation for this can be found in what many subjects reported during the experiment: in AR, more pellets were needed for aiming and orientation since the virtual bullets did not always match 100% with the real pistol's muzzle. In VR, the overall visual impression was considered to be more consistent. Both the execution time and the shots needed are more leptokurtic by a lower standard deviation in VR, so it actually appears to be the slightly steadier variant.

The personal experience with 3D applications in general and 3D shooter games in particular had no statistically significant influence on the individual result. Hand-eye coordination when shooting with a real pistol in six degrees of freedom is probably too different from shooting with a computer mouse and two degrees of freedom on a desktop. This would need more investigation and a more appropriately differentiated selection of participants.

		Augmented Reality		Virtual Reality	
		Mean	Std. Dev	Mean	Std. Dev.
Overall (N=40)	Execution Time [ms]	3378.04	896.55	3306.56	925.39
	Shots Needed [float]	3.71	1.01	3.17	0.99
3D experienced (N=22)	Execution Time [ms]	3134.69	741.28	3067.66	751.7
	Shots Needed [float]	3.59	0.87	3.05	1.05
3D inexperienced (N=18)	Execution Time [ms]	3681.45	995.57	3598.61	1049.94
	Shots Needed [float]	3.86	1.18	3.30	0.94

Table 2: Means and standard deviations of dependent variables (execution time and the shots needed) for all users, for users experienced and inexperienced with 3D desktop applications.

7.2 Frequency Distribution of the Shot Count

The frequency distribution for VR is more platykurtic (has negative kurtosis) and shows fewer and less extreme outliers than for AR. There have been obviously more situations where an extremely surpassing amount of pellets was needed to finally hit the target in AR.

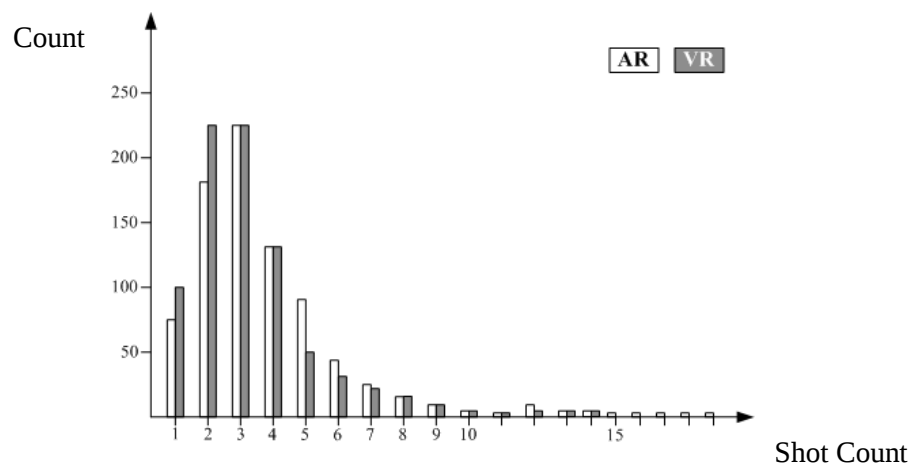


Figure 4: Frequency distribution of shots needed to hit a relic in AR and VR

7.3 Regression Analysis

Figure 5 shows the scatter plots of the tracked execution time over the individual *ID* for each target. The coefficient of determination turned out to be fairly low for AR ($R^2_{AR}=0.133$) and VR ($R^2_{VR}=0.085$). However, the F-ratio (quotient of the mean squares for the model and the residual mean squares) supports significance of the model with $F_{AR}=36.0$ ($p < 0.001$) and $F_{VR}=57.87$ ($p < 0.001$). The t-ratio (quotient of explained and unexplained variance) which is $t_{AR} = 6.0$ ($p < 0.001$) and $t_{VR} = 7.6$ ($p < 0.001$) shows that the *ID* contributes significantly to the time needed to hit a target.

We get a positive slope in both cases, but the gradient is higher for AR, so the execution time increases more with growing *ID* in comparison to VR. Finally, there are more extreme outliers in AR which correlates with the general pellet consumption.

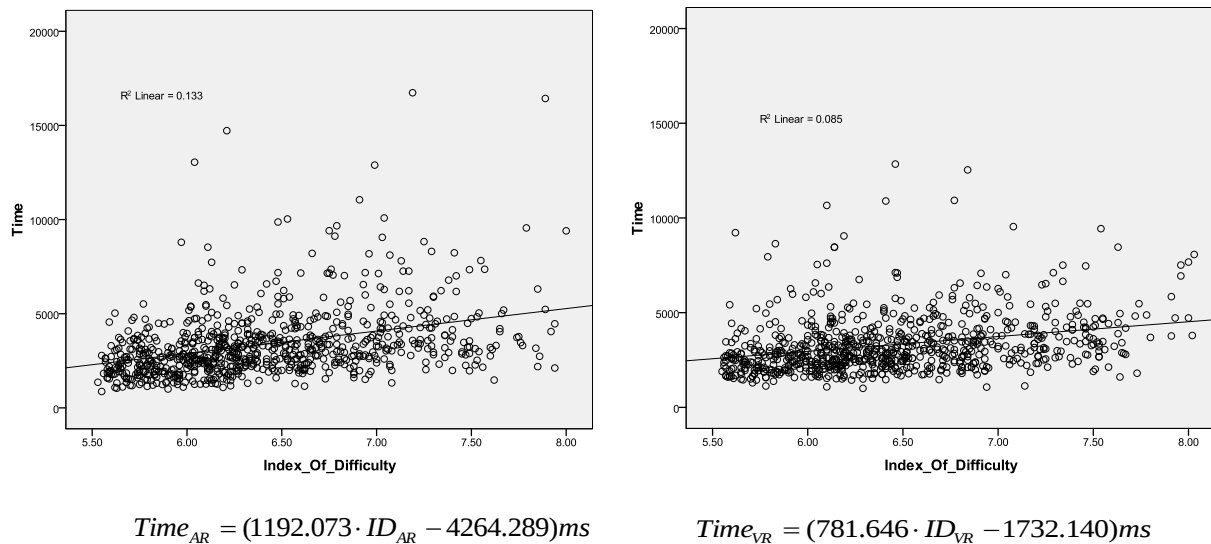


Figure 5: Scatter plot for AR and VR in comparison with regression lines and equations

7.4 Workload

To measure the individual workload impact on the user, the NASA-TLX questionnaire has been handed out to the subjects directly after an experimental run (see table 3). The independent t-test shows that there is no significant difference in any of the subscales between AR and VR, so the task load index is very similar each time. Both the mental and the physical stress have been evaluated to be of minor impact (3.0 or less in average) which is remarkably good for an HMD-based virtual reality system. Main reasons for this could be

- The brevity of the experiment (not more than 45 minutes per subject).
- The fixation of the HMD to prevent excessive head/neck exposure.
- The system design (quick calibration, easy-to-use input device), abetting short vocational adjustment.

Performance and effort indices around 5 attest a moderate and balanced degree of difficulty of the task. Even more important, the average rating on frustration was marginal (index of 2.5 in overall average) although no new relic was generated unless the current was not hit even in difficult cases where the target was extremely small and far away.

	NASA-TLX Subscales											
	Mental		Physical		Temporal		Performance		Effort		Frustration	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Overall (N=40)	2.9	2.1	2.3	1.9	4.1	2.5	5.4	1.8	5.1	2.0	2.5	2.1
AR only (N=20)	2.8	2.3	2.4	2.1	3.9	2.4	4.9	2.1	4.8	2.4	2.8	2.5
VR only (N=20)	3.0	2.0	2.2	1.7	4.4	2.6	5.8	1.3	5.4	1.6	2.2	1.5

**Table 3: NASA-TLX results in both configurations together (overall), for AR only and for VR only
(M = Mean, SD = Standard Deviation)**

7.5 Personal Preference

The personal preference was on the side of AR: 62.5% of the subjects (70% of the female and 55% of the male participants) stated to prefer working with the AR configuration rather than with VR configuration when thinking of regular usage. As a motivation, subjects who preferred the purely virtual variant liked the consistent overall impression of VR. Advocates of AR, however, did like the mixed reality approach as such and fancied the absence of latency in their own movements since the real pistol and all body parts were immediately visible in the see-through mode. For those participants, cut backs in their own performance were acceptable for the benefit of a plus in contiguousness of reality.

8.0 CONCLUSIONS AND FUTURE WORK

AR actually shapes up as a serious alternative to VR for this use case of virtual pellet blasting in a human-robot cooperation scenario with real-time physics simulation. The fact that the majority of subjects did personally favour AR supports this idea. Results of the NASA-TLX questionnaire prove a good usability of the system, highly motivating and with moderate ergonomic impact. Height-fixation the HMD for conditional equalization brought about an ergonomic advantage at the same time and the hydraulically adjustable seat has been evaluated to be significantly adjuvant at this point. The tie in execution time entails a plus of 17% in pellet exhaustion on the AR side. Statistically, this factor is significant, but practically, it is negligible since in reality, the pellets are exhausted in a salvo-wise manner. Consequently, turning from single pellet exhaustion to salvo-wise exhaustion of smaller pellets will be the next step in development, as well as implementation of side-effects like obfuscating steam.

Fitts' Law has shown rather limited power for prediction of executions times in virtual abrasive cast part blasting in its general Shannon formulation of equation (1). Although the regression analysis brought about a significant correlation between the *ID*, spawned by the size and distance of the targets and the execution time, the coefficient of determination is too unincisive. Two main reasons for this could be that the visual feedback is not continuous and so the task is not a typical Fitts' Law task and that the pellet's trajectories had non-linear characteristics. For the visual feedback, salvo-wise exhaustion of pellets could help.

The current system includes a simple human-robot monitoring approach based on the infrared tracking system which allows triggering robotic motion between five distinct postures in a coincidental sequence. Methods of artificial intelligence could be ideal to implement a more sophisticated behaviour of the robot, possibly also adapting human laboring strategies.

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