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Abstract:	In the last decade, Augmented Reality has become increasingly popular. As improved performances are gathered in terms of mature hardware and software tools, we are observing the stemming of a huge number of applications of this technology both in the entertainment and in the industrial domains. On the one hand, such applications are usually claimed to bring benefits in terms of productivity or enhancement of the human's capability to perform tasks. On the other hand, researchers and developers seem not to adequately consider the different meanings that AR assumes when implemented through visualization devices that can differ significantly in nature and in their capability to provide a mixed real-virtual scenario. In this paper, we describe a user-centred method based on an integrated QFD-AHP approach to select the best visualization display technology with regard to a specific application context. The aim is to establish a repeatable and documented process for the identification of the technology that best suits and mitigates the acceptability risks of the transition from a legacy working environment to an AR based operational environment. The method has been developed in the framework of the RETINA (Resilient Synthetic Vision for Advanced Control Tower Air Navigation Service Provision) project involving the end users, in this case, air traffic controllers. Nevertheless, it can be generalised and applied to other contexts of use. Furthermore, in order to be resilient to the fast, technological development in AR, it can be used to update the results as improvements arise in the performance level of the display devices in a specific technology. Keywords: Augmented Reality, Air Traffic Control, Quality Function Deployment (QFD), Analytic Hierarchy Process (AHP), Human Machine Interface.

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Keywords: Augmented Reality, Air Traffic Control, Quality Function Deployment (QFD), Analytic Hierarchy Process (AHP), Human Machine Interface.

1. Introduction

Augmented Reality (AR) differs from Virtual Reality (VR) as AR enriches the physical world around the user, while VR completely obscures it and immerses users in a fully artificial digital environment [1] [2]. In other words, AR is the real-time superposition of computer-generated data and images directly onto the real world. Such computer-generated data, properly designed and overlapped on the real scene seen by the user, offer the possibility to augment the human's perception capability. The benefits brought by Augmented Reality have been demonstrated in several applications, such as Entertainment, Education, Maintaining and Repair, Military and others [3]. In this context, one of the most promising fields is the transport sector and specifically the implementation of AR in innovative Human Machine Interfaces in this domain. For example, several studies and prototypes have been proposed, experimented or even implemented for the automotive, the maritime or the aeronautical domains [[4]][[5]]. Among these application studies, we can identify two main operational functions in which the AR applications in transport can be classified, namely the provision of navigation aids and support in control and management.

The first type of function tackles the issue of guidance to a destination while driving or piloting a vehicle, even in scarce visibility conditions or beyond the line of sight. As an example, we can consider the Head-Up Displays that were conceived for pilot assistance in military aircraft and have been analysed extensively in terms of benefits and drawbacks in cognitive aspects [[6]]. Currently, the automotive sector represents the leading transport industry in terms of investments in Augmented Reality-based navigation aids: digital overlays can be applied on the car windshield to inform the driver of the car's speed, where to turn, the location of lane markings and the distance from the car ahead [[7]].
As far as the control and management support function is concerned, it is usually characterized by the presence of an observer experiencing a panoramic view of the surrounding environment, which must be managed and controlled. This is the case of the control centres managing airports, ports and container terminals. The use of AR in these facilities is expected to bring significant benefits in terms of decrease to the operators' workload as well as performance and situation awareness improvement, providing a positive impact on the safety and efficiency of the whole system [[8]][[9]].
Augmented Reality can be implemented through different kinds of devices, ranging from hand-held devices to See-Through HMDs (Head Mounted Displays). Nevertheless, it is surprising that the application studies rarely adopt a user-driven approach to select the type of device that best complies with the operational context and the user requirements in each specific case.
This paper aims to propose a method for the user-centred selection of the right AR visualization technology in industrial applications based on an integrated AHP-QFD approach. The method has been built upon a case study in the control and management support operational domain. Specifically, it has been conceived and applied to the Air Control Tower AR technology selection process in the framework of the RETINA Project. Retina is a SESAR Horizon 2020 Exploratory Research European Project dealing with Augmented Reality for airport control towers. The project's main aim is to investigate the applicability and the potential benefits, with regard to safety and efficiency aspects, of Augmented Reality display techniques for the Air Traffic Control (ATC) service provision in the airport control tower [[10]] [11][12][13]. The first phase of the project was devoted to the selection of the display technology for the application and it was performed through the active participation of potential end users. To this end, a review of the AR display technologies currently available and classified according to Bimber and Raskar was initially conducted. Afterwards, this list of technologies was used as the input of the selection process. In the following sections, an insight into the Retina project is provided, followed by the critical review of the available technologies, while the user-centred selection process is described in detail in the Materials and Methods section. Finally, results gathered from the implementation of the method in RETINA are reported, and a discussion is provided.

2. AR for Airport Control Towers

The Retina Project started in 2016 and successfully concluded in February 2018. It was coordinated by the Department of Industrial Engineering of the University of Bologna (UNIBO) and the consortium included CRIDA (Spanish centre for research, development and innovation in the Air Traffic Management field), ENAV (the Italian Air Navigation Service Provider), EUROCONTROL (The European Organisation for the Safety of Air Navigation) and LUCIAD (supplier of geographic information system (GIS) and high performance geospatial situational awareness tools).
The project motivations were the following:
1) With the introduction of automation, the Air Traffic Control Operator's (ATCO) attention has been progressively drawn from the out-of-window view of the tower, as most information is now available on the head-down monitor inside the control tower. This interface increases workload and reduces controllers' situational awareness since it forces them to repeatedly switch their gaze between the head-down equipment and the out-of-window view. On the other hand, Augmented Reality offers the opportunity of moving information from the head-down interface to the head-up view, by means of

digital transparent overlays, representing flight tags, aircraft bounding boxes, airside layout and runway status superimposed over the out-of-window view (Figure 1).

Figure 1 the RETINA Project concept following the legacy and the current system architecture

2) In the current systems, some specific procedures are applied to maintain safety as visibility decreases. Such procedures are based on limitations that have a negative effect on the airport throughput. RETINA aimed to provide controllers with a synthetic view of the traffic and airport layout not subject to limitations dictated by weather or distance, thus preserving situational awareness even in low visibility conditions (Figure 2). This could lead to the removal of most limitations with a positive effect on the airport throughput, leading also to subsequent positive impacts on costs and the environment.

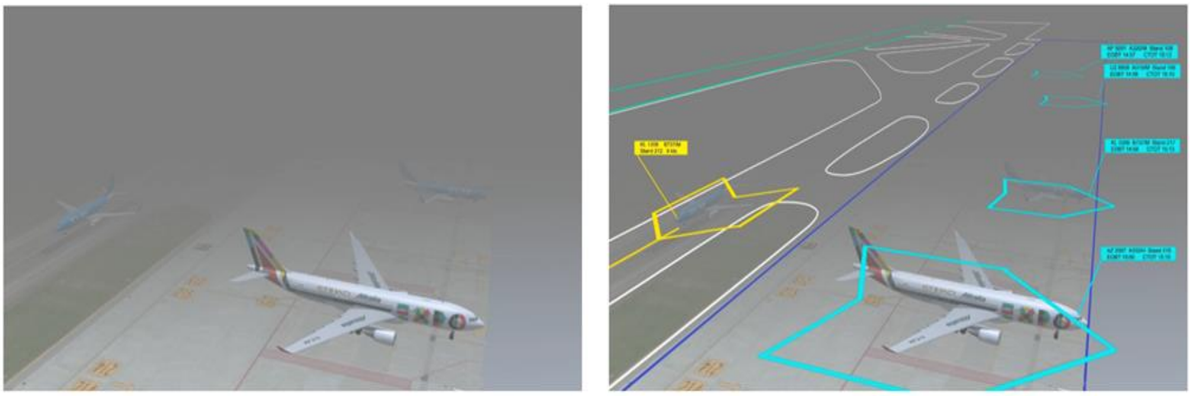


Figure 2 Out of the tower window view without and with Augmented Reality overlays

The main aim of the project was to demonstrate the positive impact of the proposed Augmented Reality tools in terms of human performance (situation awareness and human factors), safety (capability to detect some typical hazardous situations such as runway incursions) and efficiency (workload and maintenance of capacity in poor visibility conditions).
The first phase of the project was to identify the display technology that best suits the application by actively involving the end users. This phase started with a critical review of the AR display technologies. Subsequently, this list of technologies was used as the input of an integrated approach that combined Quality Function Deployment (QFD) and Analytic Hierarchy Process (AHP) methods and involved a focus group of Air Traffic Controllers.

3. The AR Display Technologies: a review

As said above, Augmented Reality can be implemented through different kinds of visualization devices, ranging from hand-held devices to See-Through HMD. One of the best-known classification criteria for such devices has been proposed by Bimber and Raskar [15]. They propose a taxonomy which is based on the location of the AR device along the optical path between the real object and the observer's eyes (Figure 3).

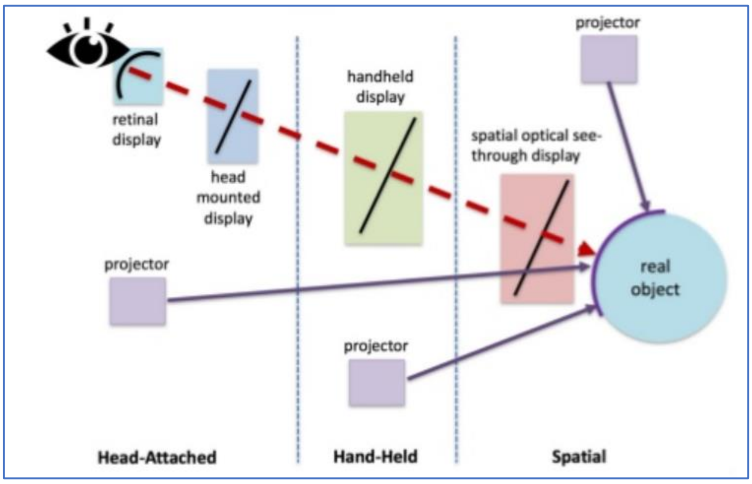


Figure 3 Classification of AR technology by Bimber and Raskar

Five types of AR technologies are considered for the study (Figure 4) and classified according to Bimber and Raskar [15]

Figure 4 AR technologies identified for the Airport Control Tower

On the one hand, the benefits of *See-Through Head-Mounted Displays* are mainly associated with customization. These are wearable devices and customized imagery can be shown to each user according to his/her tasks with a visual efficacy that is not related to their position. On the other hand, the drawbacks of *See-Through Head-Mounted Displays* can be summarized in intrusiveness, due to the weight of the helmet, negative impact on teamwork, communications and information-sharing with other interested colleagues given that personal devices can isolate the user from others. Moreover, reduction in peripheral vision is still considered an issue, since the field of view of such devices is currently limited compared to the total observable area for a human.

See-Through Spatial Displays are large screens that can be used by multiple users simultaneously (detached from the user and integrated into the environment), i.e. large conformal head-up displays that would coincide with the control room windows. Such technology is intended to provide 3D perception, without the need for special glasses or other headgear. Although not currently available on the market, *Spatial Displays* may resolve some of the shortcomings related to body-attached displays, providing improved ergonomics due to the absence of wearable devices and an unrestricted field of view as well as producing the subsequent positive impact on teamwork. The drawbacks of *Spatial Displays* concern the issue of the presence of multiple users. In order to collimate the AR overlays to the real scene, each user needs to look at overlays that are consistent with his/her viewpoint, filtering out the overlays dedicated to the other users' viewpoints. Thus, it is necessary to adopt a technology that can selectively provide different visual channels to multiple users using the same visualization device. The same technology, when available, will lead to the customization of the information provided to the specific user based, for instance, on the control role he/she is assuming.

Hand-Held Displays are fully mature devices. Tablets and smartphones are relatively inexpensive, and many video-based AR applications have already been developed for these platforms. Nevertheless, a limitation lies in the fact that the user has at least one hand occupied, and this can become an inconvenience for the use of this type of technology in several operational scenarios, e.g. Control Towers. In addition, the physical effort necessary to hold the hand-held device for a long time must be taken into account as a limiting factor. Finally, the portion of the viewing field where the user can have augmentation is rather narrow for such devices.

Object-Projected Displays are systems where the imagery is directly projected on the real world objects (the object itself becomes the canvas of the AR image generator); the light source (alias the projector) can be attached to the user's head, held within the hand or positioned in space. The maturity level of such technology is rather low. In fact, it is difficult to set up a projection system which can handle different types of objects and VR/AR contents at the same time. Therefore, the risk of having to set up a very customized configuration is quite high. The main benefit of *Object-Projected Displays* is a high level of integration with the viewer's tasks within the working environment. This feature makes this technology perfect for close range and manual applications such as AR maintenance, assembly and installations, as well as for some video-ludic applications. However, the display area is constrained to the size, shape, and colour of the physical objects' surfaces (for example, no graphics can be displayed beside the objects' surfaces if no projection surface is present) and limited by the capabilities of the projection system. Furthermore, there is no standard procedure for the generation of the AR content.

Finally, as far as *Volumetric Displays* are concerned, a visual representation of an object in 3D is formed, as opposed to 2D of traditional screens. Such technology creates 3D imagery via the emission, scattering, or relaying of illumination from well-defined regions in a 3D space. Holographic and highly multi-view displays can be considered *Volumetric Displays* if they do a reasonable job of projecting a three-dimensional light field within a volume. Other less-used versions display a more holographic image that can be created on top of a table, without a holding volume or medium.

Volumetric Displays are still under development and have yet to reach the general population. With a variety of systems proposed and in use in small quantities—mostly in academia and various research labs—*Volumetric Displays* remain accessible only to academics, corporations and the military.

The benefit of such technology is the ability to see the virtual data in 3D, as well as to allow more than one user to visualize the data at the same time. The drawback is that the visualization is displayed in a fixed location, usually on a desktop or in a ball like volume and draws the controllers' attention away from the out-the-window view, which is what the project is trying to reduce. Moreover, similarly to Spatial Displays, each user needs different registration according to his/her position without seeing information registered for the other user, so that it may be difficult for the application to adapt to the context of a specific user.

4. Materials and Methods

As stated above, the technology selection process is based on an integrated approach that combines Quality Function Deployment (QFD) and Analytic Hierarchy Process (AHP) methods. In particular, the procedure considers only a part of the whole QFD process, namely the House of Quality (HOQ). The integration of the AHP in the House of Quality matrix aims to make the HOQ method - that is wellrecognised as supporting developers and decision makers in prioritising alternatives - more robust and reliable.

As is known, the QFD model starts with the identification of a list of product or system requirements from the user's perspectives and correlates each requisite to measurable performance parameters in a correlation matrix which is the core of the HOQ diagram [16]. In this case, the "product" is intended to be the best technology, selected among the list of available display techniques for the implementation of AR in the Air Control Tower. In addition, AHP offers a method based on pairs comparison, and not absolute score assignment, to compute the weights of the user's needs and to rank such technologies.

Therefore, the Requirements represent what the technology must do, and the Technical Measures describe how the technology might be implemented to fulfil such requirements. Thus, similarly to what Rajesh et al. did for suppliers' selection [17], in our case, a QFD-AHP Integrated model has been considered to select the Augmented Reality Technology that best suits the requirements posed by the RETINA operational concept, i.e. an Augmented Reality-based Airport Control Tower. The integrated model is represented in Figure 5.

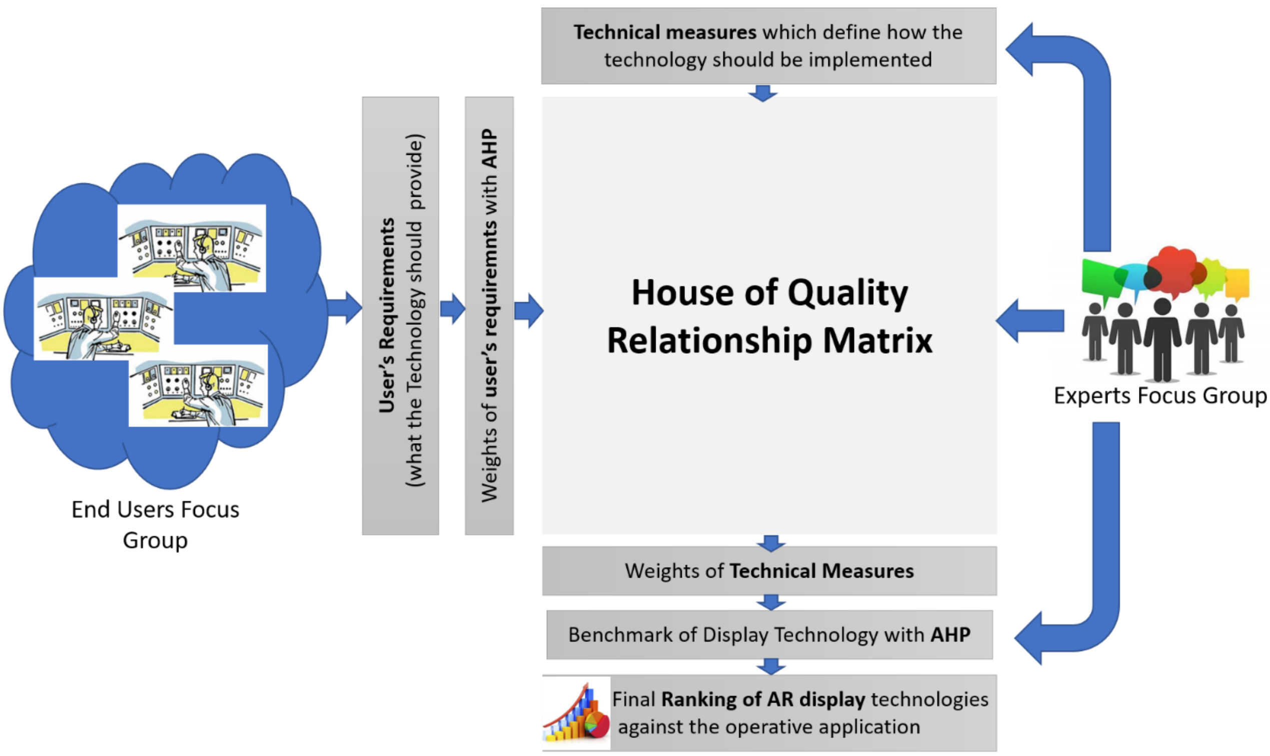


Figure 5 The Integrated QFD-AHP Model

4.1 Requirements and related weights using AHP

Requirements are largely independent of any specific technology we might develop: a team should be able to identify customer needs without knowing how those needs will be addressed. The user's requirements (Table 1 User's requirements were collected through a survey submitted to an End Users Focus Group composed of ten professional ATCOs.

User's Requirement	***Meaning***
Precision	The AR Overlay should be seen where expected on the real-world scene

Reactivity	No latencies in the update of the overlays should be observed when moving the point of view in the real-world scene
Clear Vision	The AR Overlay should be clearly visible in every working condition
Comfort	The use of the visualization device should be comfortable
Flexibility	Changes in the airport layout and procedures should be easily implemented
Scalability	The system can be easily improved and scaled
Customization	The system can be adapted to controller's needs
Ease of setting up	Set-up time and effort should be as short and as little as possible
Intuitiveness	No need for extensive training
Cluttering Reduction	Avoid high graphic density
No overlapping images for controllers performing different tasks	In case of multiple users AR overlays should be filtered by user

Table 1 User's requirements collected within an End Users Focus Group

The ATCOs were then asked to fill in the comparison matrix of requirements to assess the priority of each Requirement with respect to the others. The assessment was based on Saaty's nine-point scale [18][18] and the prioritization of requirements was derived in terms of requirements' relative weights (Figure 6)

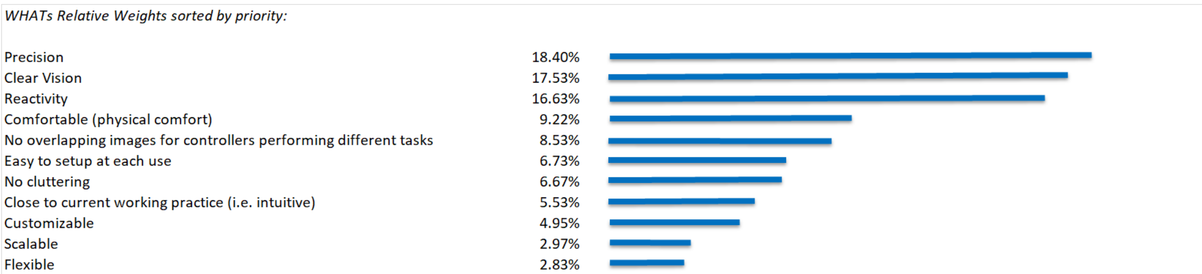


Figure 6 The mean value of requirements' relative weights collected in the survey

The results highlight that -according to the ATCOs - Precision, Clear Vision and Reactivity were the three most important requirements, accounting for more than 50% of the total share. These were followed by requirements of physical comfort and the absence of overlapping images, that were almost 50% lower when compared to the first positions. The other six requirements were characterized by values in the range of 3% to 7% and together represented less than 30% of the total weight (100%), showing that ATCO stakeholders attributed little importance to them.

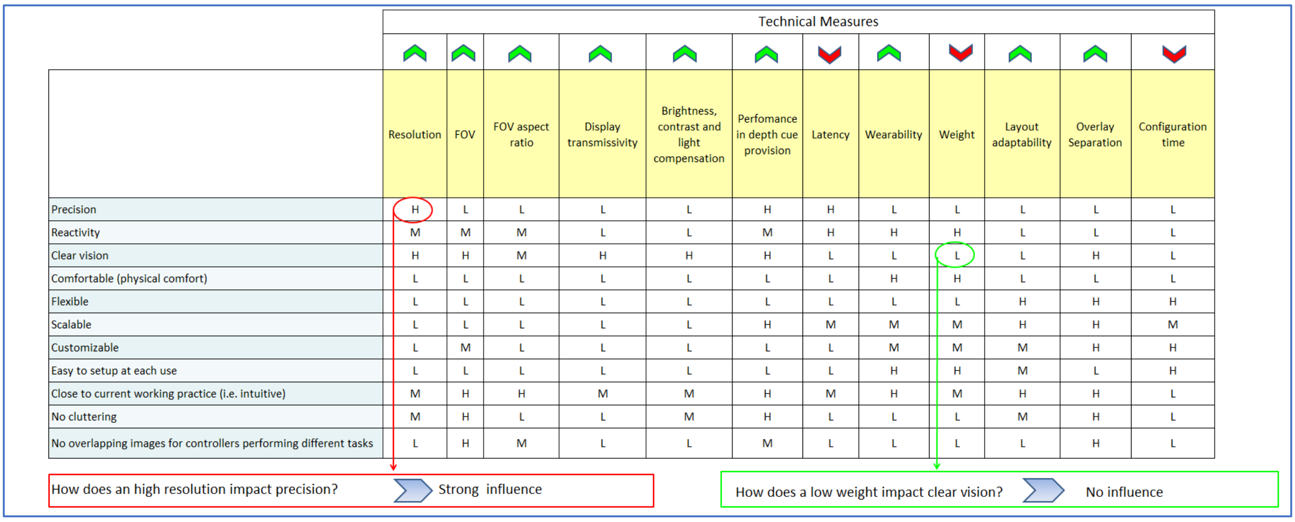
4.2 Determination of Technical Measures, Relationship Matrix and Calculation of Weights for the Technical Measures

The list of technical measures has been elaborated by a focus group within the project consortium. The resulting twelve Technical Measures were identified to fulfil the requirements, as represented in Table 2

Technical Measures	***Meaning***
Resolution	The ability of an imaging system to resolve detail in the object that is being imaged
FOV	Field of View
FOV Aspect Ratio	Ratio between vertical FOV and horizontal one
Display transmissivity	Display opacity. If transmissivity increases, opacity decreases
Brightness, contrast and light compensation	Compensation for tower lighting conditions. They could change from window to window
Performance in depth cue provision	Monocular, binocular, biocular
Latency	Virtual image delay with respect to real image
Wearability	Intrusiveness
Weight	Weight
Layout adaptability	Adaptability to airport layout changes
Overlay separation	The system is able to provide separated overlays for different users
Configuration time	Configuration time at the beginning of each working session

Table 2 Technical Measures identified within a focus group

The same approach was adopted for the HOQ Relationship Matrix. Therefore, the impact of each Technical Measure on each Requirement (i.e. the values of the Relationship Matrix) was first recorded as High, Medium and Low. The resulting matrix is shown in Figure 7.



	Technical Measures											
	Resolution	FOV	FOV aspect ratio	Display transmissivity	Brightness, contrast and light compensation	Perfomance in depth cue provision	Latency	Wearability	Weight	Layout adaptability	Overlay Separation	Configuration time
Precision	H	L	L	L	L	H	H	L	L	L	L	L
Reactivity	M	M	M	L	L	M	H	H	H	L	L	L
Clear vision	H	H	M	H	H	H	L	L	L	L	H	L
Comfortable (physical comfort)	L	L	L	L	L	L	L	H	H	L	L	L
Flexible	L	L	L	L	L	L	L	L	L	H	H	H
Scalable	L	L	L	L	L	H	M	M	M	H	H	M
Customizable	L	M	L	L	L	L	L	M	M	M	H	H
Easy to setup at each use	L	L	L	L	L	L	L	H	H	M	L	H
Close to current working practice (i.e. intuitive)	M	H	H	M	M	H	M	H	M	H	H	L
No cluttering	M	H	L	L	M	H	L	L	L	M	H	L
No overlapping images for controllers performing different tasks	L	H	M	L	L	M	L	L	L	L	H	L

Figure 7: The relationship matrix and Technical Measures impacts on Requirements

Subsequently, the numerical values of 9, 3 and 1 were assigned to High, Medium and Low impact, respectively. The unbalanced gap between 9 and 3 (with respect to 3 and 1) was chosen to assign more importance to the best impacts.

Finally, the relative weights of each Technical Measure were computed by means of (1):

$$w_{TM_j} = \frac{\sum_{i=1}^{n} w_{R_i} * imp_{TM_j \rightarrow R_i}}{\sum_{i=1}^{n} \sum_{j=1}^{m} w_{R_i} * imp_{TM_j \rightarrow R_i}} \quad (1)$$

where:

w_{TM_j} = relative weight of the *j*-th Technical Measure

n = total number of Requirements

m = total number of Technical Measures

w_{R_i} = relative weight of the *i*-th Requirement

$imp_{TM_j \rightarrow R_i}$ = impact of the *j*-th Technical Measure on the *i*-th Requirement

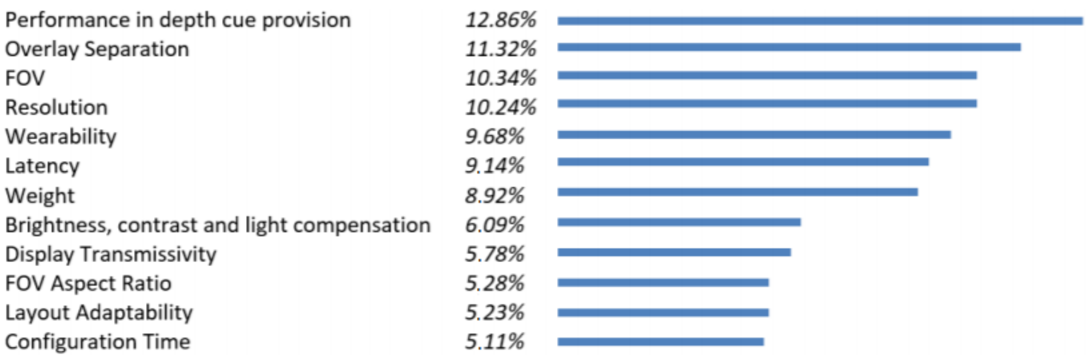


Figure 8 Relative weight of each Technical Measure

Scores in Figure 8 reveal a ranking divided into three main areas:

1.Performances in depth cue provision and Overlay Separation are the most impacting Technical Measures.

2.FOV, Resolution, Wearability, Latency and Weight are very close to each other, as the difference between the higher (FOV) and the lower (Weight) is less than 1.5%.

3.Finally, the technical measures that were assessed as less important were Brightness, Contrast and Light Compensation, Display Transmissivity, FOV Aspect Ratio, Layout Adaptability and Configuration Time.

5. Results

After a thorough discussion, the experts in the focus group provided a benchmark of the five display technologies regarding every single technical measure using the AHP model and the aforementioned 9-point scale. The comparisons focused on the current average performance of the five generic classes of technology usable in an airport control tower operational environment and on predictions on possible improvements of such devices in the near future. In cases where the technology is not yet available, such as Spatial Displays, its forecasted performance in a one-decade timespan was considered in the evaluation.
This analysis can be subsequently updated to consider the real evolution of the technologies considered.

As far as the first two most-impacting Technical Measures are concerned, namely "Performances in depth cue provision" and "Overlay Separation", the related comparison matrices are reported in Figure 9. Similar comparisons were conducted for all the technical measures cited above and are reported in [19][19].

Performaces in depth cue provision	Head-Mounted Displays	Spatial Displays	Hand-Held Displays	Object-Projected Displays	Volumetric Displays
Head-Mounted Displays		-3	5	5	7
Spatial Displays			7	7	9
Hand-Held Displays				1	3
Object-Projected Displays					3
Volumetric Displays	Matrix Inconsistency: 0.04				

Overlay Separation	Head-Mounted Displays	Spatial Displays	Hand-Held Displays	Object-Projected Displays	Volumetric Displays
Head-Mounted Displays		7	3	9	8
Spatial Displays			-5	3	2
Hand-Held Displays				7	6
Object-Projected Displays					-2
Volumetric Displays	Matrix Inconsistency: 0.04				

Figure 9 Technologies comparison matrices and rankings for Depth Cue Provision and Overlay Separation Technical Measures, using AHP model

The first matrix shows that Spatial Displays perform better than any other display technology in Depth Cue Provision. Head-Mounted Displays (HMDs) were evaluated as much more efficient than Hand-Held and Object-Projected Displays, given that Tablet PCs, PDAs (Personal Digital Assistant), smartphones and video-projectors are characterized by a very rare capability to display images in 3D. On the other hand, Spatial Displays were considered slightly better than HMDs for the Air Traffic Control service provision by the airport control tower, since the latter are generally expected to be characterized by a longer working distance (the extensive experience gained in the aircraft cockpit head-up displays can serve as an example in this regard), so that they suffer from vergence-accommodation conflict less than HMDs. Volumetric Displays have been evaluated as the least efficient technology since the visualization in those systems is concentrated in a fixed location, usually on a desktop or in a ball-like volume, drawing the controllers' attention away from the out-of-window view.
As far as the Overlay Separation is concerned, the focus group agrees that HMDs perform significantly better than other technologies. In fact, they can be fully customized for the single user as they are typically personal devices that follow the user within the working environment. Moreover, customized imagery can be shown to each user according to the task to be accomplished with a visual efficacy that is not connected to position. Furthermore, it does not impair the view of other users, thus controllers are not distracted by irrelevant information and their situational awareness is improved. Hand-Held Displays show a very similar behaviour by pointing the device towards the interest area of the task, but they were evaluated moderately less efficient as they are less immersive than HMDs. Volumetric and Spatial Displays were evaluated as much less efficient than HMDs with respect to the Overlay Separation, since they are used by multiple controllers simultaneously; hence it may be very difficult to adapt them to the context of a specific user (especially for Volumetric Displays, where overlays are confined in a less extended area). Finally, Object-Projected technology adds many more variables to the overlay separation problem: the display area is constrained to the size, shape and colour of the physical objects' surfaces. This characteristic makes them extremely less efficient than HMD technology. It is significant to highlight that the efficiency of the overlay separation decreases when the distance between the eyes and display area increases.

Finally, the scores gathered by technologies were multiplied by the relative weight of each technical measure, obtaining the following final ranking of technologies (Figure 10):

Figure 10 Final ranking of the Augmented Reality Technology

Apart from Head-Mounted Displays, other technologies obtained about half the score or less than Spatial Displays. The results obtained by the last three technologies in the ranking list are very close to each other, as the difference between the technology ranked third (Hand-Held Displays) and the bottom one (Volumetric Displays) is roughly 2.2%.
Thus, the Integrated QFD-AHP model evaluated the Spatial Displays (which are supposed to coincide with the Control Tower windows), as the preferred technology solution since they were considered more efficient than competitors in almost every Technical Measure examined in the analysis, especially in the most influential ones, as illustrated in Figure 11 that shows a graphical analysis of the above-obtained results, reporting the scores (y-axis) gained by the technologies analysed against the specific technical measure (x-axis).

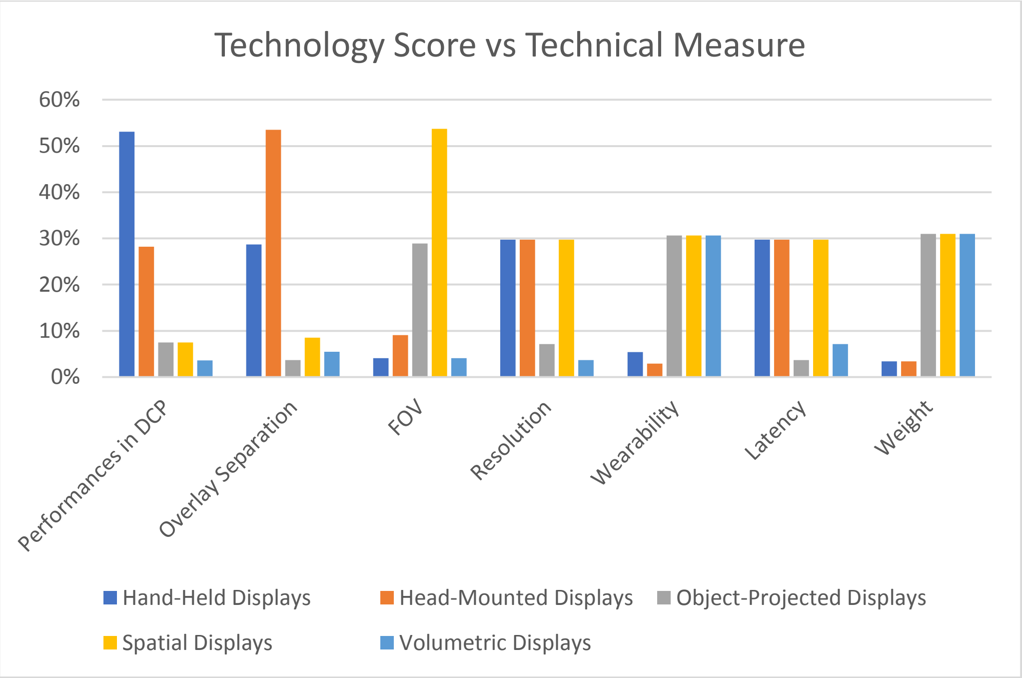


Figure 11 Technology scores for each technical measure

6. Conclusions

The target of the analysis reported in this article was to select the most efficient Augmented Reality technologies for the Air Traffic Control service provision by the Airport Control Tower, integrating the "out-of-window" real images with a 3D digital model (concerning airport layout, precise positioning for both aerial and terrestrial objects and meteorological data) and providing tower controllers with:

- unlimited vision (by either weather or distance)
- and only relevant information to be displayed on a single head-up view.

To this aim, five augmented reality technologies – i.e. Spatial, Head-Mounted, Hand-Held, Object-Projected and Volumetric Displays – were compared.
The selection process was based on an integrated approach that combines the House of Quality (HOQ) method and the Analytic Hierarchy Process (AHP) in order to make the HOQ technique more robust and reliable to decision makers.
The output of the integrated model generated the following technology ranking: Spatial Displays, Head-Mounted Displays, Hand-Held Displays, Object-Projected Displays and Volumetric Displays, with the first two technologies in the ranking list outperforming the last three.
Thus, the selected technologies are the Spatial and Head-Mounted Displays, while Hand-Held, Object-Projected and Volumetric Displays do not seem to fit complex applications such as the provision of the ATC service by the control tower.

Finally, it should be noted that the selection process was based on current average performances of the five generic classes of technology usable in the control tower environment, as well as on predictions of the possible improvements of such devices in the near future. For what concerns Spatial Displays, this type of technology is not currently available so its forecasted performance in a one-decade timespan was considered.

This analysis could be subsequently updated, considering further development in technology and more specific devices within the five generic classes.

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