More Arrows in the Quiver: Investigating the Use of Auxiliary Models to Localize In-View Components with Augmented Reality

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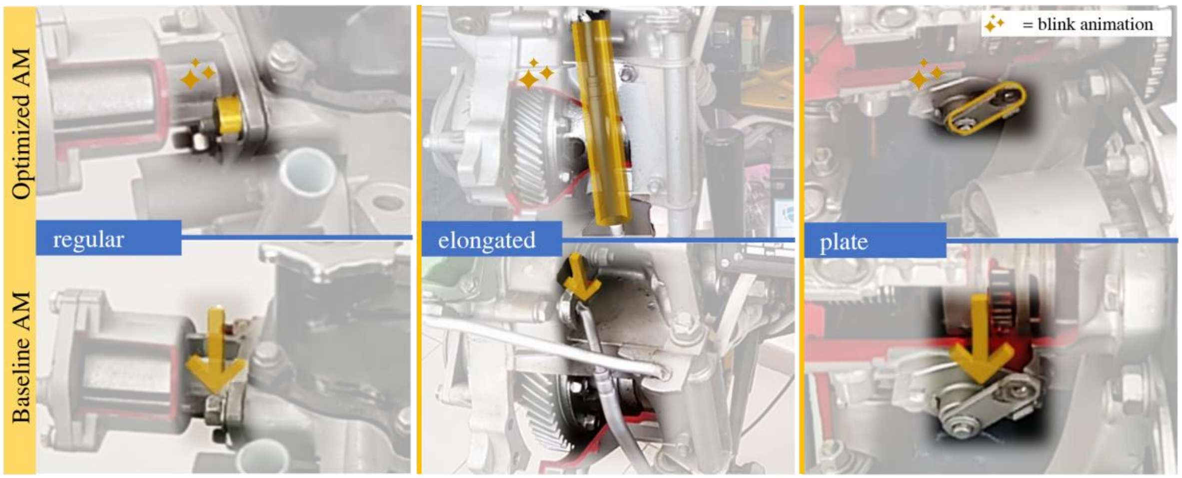

Fig. 1. We proposed validated guidelines for the design of auxiliary models according to the shape of the component to localize. The figure shows the second user study in which we validated the optimized auxiliary models against 3D arrows (baseline), which are widely used to localize components in AR interfaces. To enhance the visibility of the component and auxiliary models in the figure, a blur effect is applied on the rest of the scene. This user study was carried out for twelve components, classified in three shape categories: regular, elongated, plate.

Abstract—The creation and management of content are among the main open issues for the spread of Augmented Reality. In Augmented Reality interfaces for procedural tasks, a key authoring strategy is chunking instructions and using optimized visual cues, i.e., tailored to the specific information to convey. Nevertheless, research works rarely present rationales behind their choice. This work aims to provide design guidelines for the localization of in-view and not occluded components, which is recurrent information in technical documentation. Previous studies revealed that the most suited visual cues to convey this information are auxiliary models, i.e., abstract shapes that highlight the space region where the component is located. Among them, 3D arrows are widely used, but they may produce ambiguity of information. Furthermore, from the literature, it is unclear how to design auxiliary model shapes and if they are affected by the component shapes. To fill this gap, we conducted two user studies. In the first study, we collected the preference of 45 users regarding the shape, color, and animation of auxiliary models for the localization of various component shapes. According to the results of this study, we defined guidelines for designing optimized auxiliary models based on the component shapes. In the second user study, we validated these guidelines by evaluating the performance (localization time and recognition accuracy) and user experience of 24 users. The results of this study allowed us to confirm that designing auxiliary models following our guidelines leads to a higher recognition accuracy and user experience than using 3D arrows.

Index Terms—Augmented reality, Localization, Authoring, Auxiliary model

1 Introduction

The localization of components is among the information which benefits more from Augmented Reality (AR) cues and is recurrent in procedural tasks such as maintenance, assembly, and training. In complex machines, many objects are close to each other. Therefore, AR localization cues may be attributed to wrong components even if they are in-view and not occluded by other objects. Then, this work aims at proposing optimized AR visual cues to overcome this issue.

Several studies [1], [2] demonstrated that AR prevents operators from memorizing instructions by providing step-by-step guidance in procedural tasks, thus reducing their cognitive load and improving the accuracy and the machine downtime. Using directly generated AR-assisted operations reduced operating costs, efficient processes, and increased company productivity. Besides these benefits, AR still lacks the robustness and flexibility to become common use [3]. Among the main open issues, it is possible to cite tracking, hardware capabilities, and contents-related issues [1], [4], [5]. In this work, we address the last topic mentioned which involves difficulties in the authoring process, i.e., creating and managing content for AR applications. Authoring AR interfaces requires highly qualified professionals [6]: programmers, animators, CAD modelers, and AR developers.

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- Manuscript received xx xxx. 201x; accepted xx xxx. 201x. Date of
- Publication xx xxx. 201x; date of current version xx xxx. 201x.
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However, there is still a lack of expert knowledge of AR in the companies. Established guidelines derived from user experience evaluation are needed for the authoring of optimized AR interfaces not only based on the designer's personal preference [7].

A key factor for a more efficient authoring of AR interfaces for procedural tasks is chunking instructions [8] and using optimized visual cues according to the specific information to convey [9], [10]. However, one of the unsolved authoring issues is the difficulty in choosing appropriate visual assets for each type of information [6], [10]. Research works rarely present rationales behind the choices of visualization methods and, when present, guidelines regarding general technical issues such as occlusion, geometric consistency, and computational cost [11].

CAD models spatially aligned with the component to be identified are widely adopted [12] in the literature for localization tasks. They could be either a virtual replica of the real component (product model) or an abstract shape (auxiliary model) that highlights the space region where the component is located [13]. Although product models are more pleasant for end users [14], they provide more information than the location one, such as the shape and the orientation of a component [9], demanding more cognitive resources by adding unnecessary clutter [15]. Auxiliary models (AMs) instead provide only the information about location. Furthermore, using AMs simplifies the authoring process because they can be easily recalled from a standard library, independent of the machine, and do not require a highly accurate alignment with the real component. On the contrary, product models need the CAD models of each machine component, which may not always be available, and require an accurate overlapping with the real component [16].

However, using AMs can lead to ambiguous interpretations of the right component to identify in complex machines. AMs that point towards the component (e.g., arrows) may indicate points attributable to more than one component, whereas AMs that delimit a region of space (e.g., a sphere) may include more than one component. In this work, we focused on in-view and not occluded objects; therefore, the ambiguity is only due to the presence of other components near the one to be localized. Using AMs optimized according to the component shape may help minimize the risk of ambiguity. Although AMs are widely used in industrial AR prototypes, the literature lacks studies on the design of AMs for locating components in complex machines. Then, in this work, we tried to answer the following research question: "is it possible to design optimized auxiliary models for locating in-view not occluded components according to their shape?"

To answer our research question, we first performed a user study where we asked participants to choose the most suitable AM for various shapes of components in a complex machine. Besides the shape of the AM, we also asked to specify other properties that may affect the localization task, i.e., color and animation. In fact, the use of contrasting colors and animations may help users draw attention to the component to be located. A first contribution of this work is then represented by the guidelines for the AM design for the localization task derived from the results of this user study. Then, we also contributed through a second user study to validate these guidelines. We evaluated user performance and user experience in the localization task accomplished with two AR interface designs (Fig. 1). We compared an interface where components are located through the AM designed according to our guidelines against an interface where components are located through 3D arrows, used as baseline.

The paper is organized into 7 sections. Section 2 reports the related work on the design variables of AMs for a localization task. In Sections 3 and 4, the design, results, and discussion of the first study and validation are reported, respectively. Section 5 discusses the overall results obtained, while Section 6 offers future research directions. Finally, in Section 7, a conclusion is provided.

2 Related Work

Our work is related to previous research on AR interfaces presenting AMs to locate objects in procedural tasks. We analyzed in separate sections the design variables of AMs considered in this research: frame of reference, shape, color, and animation. Finally, we discussed the main insights that can be derived from the literature about the design of AMs for localization tasks.

2.1 Frame of reference

The localization information can be provided using visual cues coded either in the egocentric frame of reference (e.g., arrows, halos, or other CAD models) or in the exocentric one (e.g., overview map, compass, world-in-miniature). Markov-Vetter et al. [17] found that egocentric visual cues, i.e., 3D-registered to the object, lead to the fastest and most reliable localization of objects because they indicate the position of target objects relative to the viewer's body axes instead of referring to other objects in the surrounding. For this reason, AMs in existing AR interfaces are almost always in the egocentric frame of reference, as revealed by Gattullo et al. [18].

2.2 Shape

The shape of an AM is the main property that determines how users process the localization information. We can distinguish AMs which point towards the component to be localized (hereinafter *pointing*) from those which delimit a region of space within which the component is contained (hereinafter *delimiting*). In both cases, we can distinguish 2D and 3D shapes.

The main example of *pointing* AMs is represented by arrows. Using 2D arrows, i.e., drawn on a 3D plane, simplifies the creation of AR instructions [16]. However, 2D arrows could not be recognized from all the points of view due to perspective effects unless they rotate coherently with the camera. This may be the main reason 3D arrows are much more used than 2D ones for localization tasks. Li et al. [19] proposed a taxonomy of the visual design of 3D arrow models: a prismatic arrow is proposed to indicate installation position and direct attention to an object. It is a shape widely used to indicate components, e.g., to be picked for maintenance operations [20]. Cylindrical arrows are also used, for example in [10], to indicate fixation points of screws and in [21] to indicate where to place a new part in an assembly sequence. Arrows are also largely used to guide users towards points of interest out of view due to the limited field of view of the device cameras, as in [22], [23]. Thus, arrows may be associated with different information in AR interfaces which may confuse users. This issue was pointed out by Lavric et al. [16], who distinguished a blue vertical 2D arrow for localization tasks from an orange horizontal 2D arrow, differently shaped, which suggests to operators how to turn their head to reach the assembly area.

2D *delimiting* AMs are simple shapes drawn on a 3D plane placed in correspondence with one of the surfaces of the component to be located, usually, the one oriented towards the user. A first distinction is between filled and outline shapes [24]. Filled shapes may block user view because they occlude a large part of the real environment. For this reason, they are mainly used in spatial AR applications to highlight the surface of a component to be handled [25], [26] while, for Head-Worn Displays (HWDs) or handheld device applications, transparency is used [27], [28]. Outline shapes can avoid the risk of occlusion. They are slightly larger than the component boundary to compensate for tracking inaccuracies [29]. The most used shapes are rectangles [30], circles [20], [31], multiple concentric circles [32], [33], and crosshairs [15], [34]. Free-hand sketches are used in remote collaboration applications [35], [36].

3D *delimiting* AMs are arranged to englobe the whole component to be located. They are less used in the literature than 2D shapes. In an AR assembly procedure, Blattgerste et al. [15] used a simple cuboid with size and color corresponding to the real object instead of a more detailed 3D model. A similar cue was used by Renner and Pfeiffer [32], who compared the cuboid with a 3D spline path starting in front of the user and ending at the target location. As the 2D filled AMs, the 3D ones may also block user view due to occlusion, especially in large objects. In these cases, either transparency is used [37], [38] or the 3D figure is rendered in wireframe [39].

In summary, previous work showed no one recommended shape to locate in-view objects in industrial AR interfaces. Arrows are commonly used and can be suitable for every component shape, but they are often used to indicate out-of-view regions and directions or movements. Therefore, their usage could imply ambiguity of information.

2.3 Color

Red is widely used for localization tasks. It is a highly visible color that stands out against most backgrounds, making it an effective way to draw attention to important information [40]. For example, Obermair et al. [20] use red circles and arrows to indicate screws and other components to remove in a maintenance procedure. Schwerdtfeger and Klinker [41] compared three types of red-colored cues for order-picking information. Other colors mainly used to locate objects in industrial AR interfaces are green and yellow. The main reason could be that they are colors that are less commonly found in industrial environments, making objects less likely to be confused with other elements. For example, Radkowski et al. [30] highlighted the part that needs to be assembled in an AR assembly procedure with a green frame. Webel et al. [42] used a yellow highlight to give spatial information about the current step to perform in an AR maintenance procedure.

The use of colored AMs can be associated with further information which could be conveyed through color coding. Red is usually associated with hazard or error, yellow with caution or warning, and green with success or completion. For example, Funk et al. [43] used green to communicate the position of the next picking bin and where to assemble the picked part, whereas they used red to communicate the picking from a wrong picking bin in a manual assembly workplace. Gruenefeld et al. [44] used a color gradient from blue to red to encode the distance of a 2D AM from the physical object it refers to. They used the cold and warm metaphor used in heatmaps, where red stands for very close and blue for far away.

A variable that may orientate designers in the choice of colors is the perception with the specific device used for the AR interface. Optical See-Through (OST) HWDs and Spatial AR limit the colors usable in AR interfaces. In an early research study with old-generation HWDs, Thomas et al. [45] suggested avoiding all cyan, orange, magenta, pink, and red intensities. In SAR, dark colors, such as blue, cast little light and, thus, are hardly recognizable [46]. Similarly, with OST devices, dark colors tend to disappear perceptually with light backgrounds [47]. Another perceptual issue with OST devices is color distortion, i.e., hue shift due to blending AR graphics with the background texture under changing lighting conditions [48]. Merenda et al. [49] evaluated the differences in user performance and color perception as user interface elements are presented on different backgrounds. They found that blue, green, and yellow performed more consistently and reliably than other generally recognizable colors. Based on this result, Ping et al. [50] chose these three colors to evaluate the effect of colors on depth perception in AR highlighting. They found that the distance estimation error with green and yellow AMs was lower than the blue.

From the literature analysis, it is possible to observe that using colors for AMs is not justified in most of the AR interfaces for procedural tasks. Designers may choose colors based on factors such as functional goals, user experience, perceptual issues, branding, and emotions they want to convey. Colors can be associated with specific information to convey, but color coding is not standardized.

2.4 Animation

Animations could be helpful to draw the user's attention to an object when it is occluded by another object [51]. The most common animation is the blinking. For example, Volmer et al. [52] proposed using an annotation that blinks every 300 milliseconds to obtain the information about the exact location of the next task. Blinking of rectangles is also the animation used by Buttner et al. [53] to recreate the effect of the attention funnel in spatial AR for picking tasks. Arrows are sometimes animated going back and forth along their axis as in [2]. "Fade" and "wipe" are other animations widely used as infographics to guide users' attention and improve user engagement [54]. Fading hides the AM once the user locates the object it refers to. However, these techniques were proposed for out-of-view objects. For example, in [23] a 3D arrow pointing to the target object gradually fades to full transparency when the user orients on the target. Bonanni et al. [55] modulated the brightness of the AM used to locate a handle to draw user attention to it. For in-view objects, a combination of a direction animation and fading can create wipe animations where the AMs gradually fade in and fade out along a specific direction [56].

Besides animated cues are largely used in industrial AR interfaces (e.g., to provide operators with a preview of the task to accomplish), AMs used for locating information are usually static. The use of animation in this context does not provide further information compared to the static version of the AM.

2.5 Summary

From the analysis of the literature, it is possible to conclude that:

- AMs are almost always displayed in the egocentric frame of reference.
- There is no one recommended shape. 3D arrows are widely used but can be associated with other information types.
- There is no one recommended color. Red, yellow, and green are the most used colors.
- Static AMs are usually preferred to animated ones.

Overall, we see a gap in understanding how AMs can be used to locate objects in AR interfaces for procedural tasks. In particular, we did not find studies addressing if a generic shape of AM (e.g., an arrow) could be used for every type of component or if this choice is affected by component shape.

3 User Study 1: Effect of Component Shape

In this study (US 1), we inquired if user preferences about AMs for a localization task can be influenced by the shape of the component to be localized or if users prefer using the same AM independent of the component. The design properties of AMs addressed through this study are shape, color, and animation. We did not consider position and orientation because, in the literature, it is evident that AMs must be displayed in the egocentric frame of reference [17], [18].

3.1 Setup and Implementation

We used the model of a car engine available at our university (Fig. 2) as a case study for our experiment. We chose this machine because of its complexity, consisting of numerous components with different shapes. We conducted the experiment in a laboratory room where the car engine was placed in the middle. We chose the Microsoft HoloLens 2 as device. Mixed Reality Toolkit (MRTK), Unity 3D Engine, and Vuforia Engine were used to implement the application. To spatially register the virtual content with the machine, an image target was designed and placed on the smooth surface of a support below the car engine. We designed a Graphical User Interface (GUI), placed on the ceiling, for the choice of AM design properties through the HoloLens. To save time and reduce the bias that could occur for interaction, the eye-tracking has been implemented to allow users to interact with the GUI.

3.2 Component Shape definition

To understand how the properties of AMs are affected by the shape of components, it is important to vary this parameter in the study. In the literature, the shape of an object is often described through its bounding box [57], [58]. Then, exploiting a CAD tool, we computed the Object-Oriented Bounding Box (OOBB) [59] of each component, i.e., a cuboid containing the entire object (Fig. 3). The center point of the bounding box coincides with the centroid of the component. At the same time, its orientation is defined by exploiting symmetry axes or functional axes of the component, such as the rotation axes of pulleys,

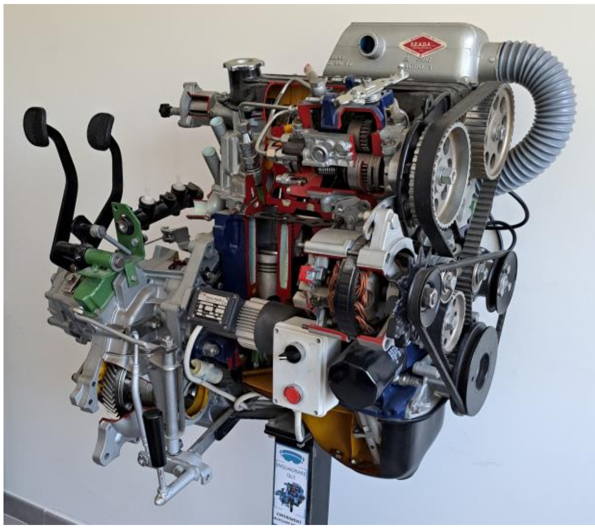


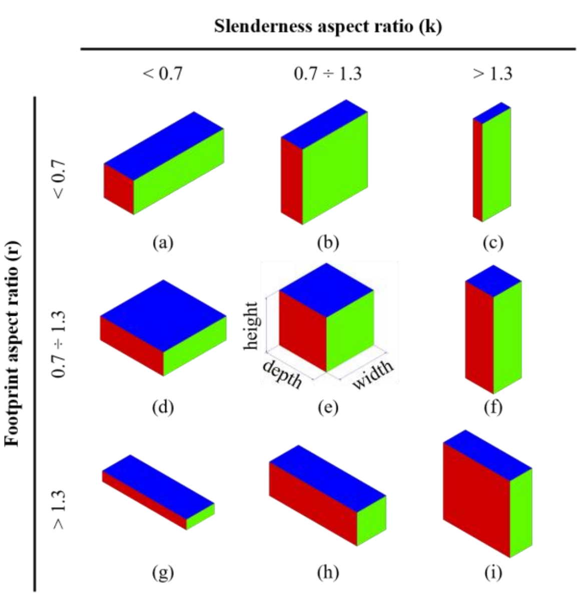
Fig. 2. Machine (car engine) used for the experiments.

motors, and screws. When it was not possible to define such axes, we referred to the main axes of the overall machine. Then, we classified the shapes of the bounding boxes according to [60], using the parameters "footprint aspect ratio" (r=depth/width) and "slenderness aspect ratio" (k=height/width). The values r=1 and k=1 correspond to a perfect cube. However, many industrial components may have a bounding box with r and k around 1, i.e., very similar to a cube but not a perfect cube. Therefore, we made a preliminary analysis of the bounding boxes of 40 different component shapes to evaluate which could be considered a cube. Based on this analysis, we decided to set a tolerance of ±0.3 for r and k, thus obtaining three intervals for the two parameters that formed the nine conditions presented in Table 1.

The bounding box for the condition "e," where both the footprint and slenderness have values around 1, corresponds to a *regular cuboid*. The conditions "a," "f," and "h" correspond to the same aspect ratio of the bounding box, only differently oriented in the space, and then were considered as one, called *elongated cuboid*. Similarly, the conditions "b," "d," and "i" were considered as one, called *square plate*, as well as the conditions "c" and "g," named *rectangular plate*.

We also considered a second parameter for defining a component shape that is similar to the bounding box. In fact, the same aspect ratio of a bounding box can be obtained either through a form that occupies a great part of it or through a form that covers it less regularly. The

Table 1: The bounding boxes for each condition ranked according to the parameters (r, k) to define the shape of a component.



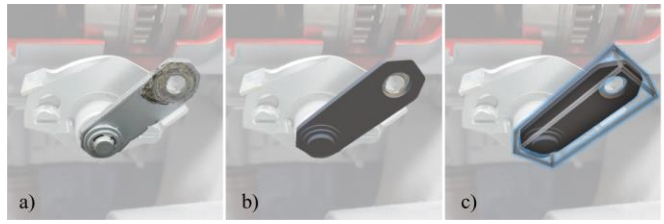


Fig. 3. For each component (a), exploiting its CAD model (b), we computed its bounding box (c) to define the shape.

geometric parameter used to distinguish these two conditions is the percentage of the volume of the component (including the volume of its cavities) with respect to the bounding box volume (V=Vc/Vb). From a preliminary evaluation of 40 different component shapes, we observed that we could consider *irregular* all those components with V<0.2. For these irregular components, the OOBB does not represent well their actual shape; then, we did not make a distinction according to the bounding box aspect ratio for them. Irregular components were considered a fifth component shape category in this study.

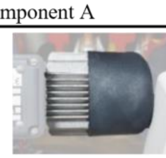
For each of the five component categories defined, we selected 2 components with different sizes from the machine engine, called "A" and "B". In this way, there were a total of 10 components involved in the localization task. The components selected from the car engine according to these constraints are shown in Table 2.

3.3 Design of Auxiliary Models

As regards the shape of AMs, we found that Paint 3D offers the widest range of 2D and 3D standard geometries. We excluded only the shapes not suitable for a localization task because they are generally used for other purposes, such as the cross, tick, heart, and cloud. On the other hand, based on the literature review, we also included 3D *pointing* AMs, i.e., the prismatic and the cylindrical arrows. The 36 selected AM shapes were classified as 3D shapes, 2D outline shapes, and 2D filled shapes [24] (Fig. 4).

In the AR environment, we designed all the AMs, setting the Unity transform properties (position, rotation, and scale) by using the bounding box centroid of each component as a reference point. Different Unity transform properties were used for *pointing* and *delimiting* AMs. The *delimiting* AMs were overlaid to the

Table 2: Components chosen for the US 1 and ranked in each category according to the parameters (r, k, and V)

	Component A		Component B	
Regular cuboid	k = 1.00 r = 1.13 V = 0.79		k = 1.00 r = 1.00 V = 0.75	
Elongated cuboid	k = 2.00 r = 0.95 V = 0.97		k = 13.33 r = 1.00 V = 0.79	
Square plate	k = 0.23 r = 1.00 V = 0.34		k = 0.15 r = 1.00 V = 0.86	
Rectangular plate	k = 1.50 r = 0.19 V = 0.92		k = 2.78 r = 0.11 V = 0.94	
Irregular	V = 0.12		V = 0.13	

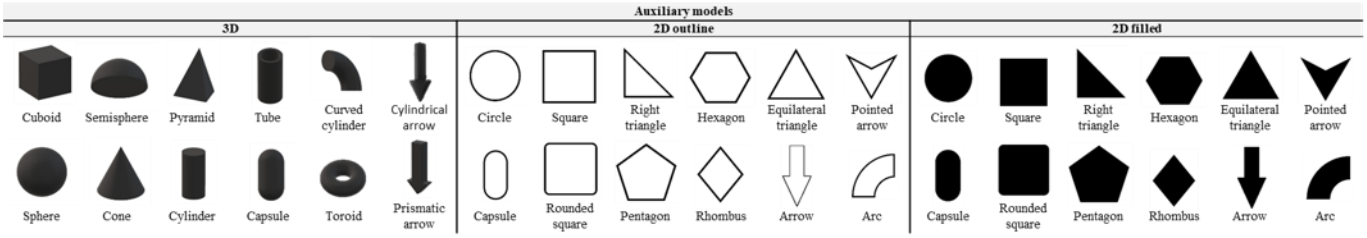


Fig. 4. The AM shapes selected for the US 1 and ranked as 3D shapes, 2D outline shapes, and 2D filled shapes.

components by matching the centroid of the AM with the centroid of the bounding box. Their scale was set to the minimum value that allowed them to englobe the bounding box of each component. *Pointing* AMs were placed above the bounding box by pointing downward its centroid, and their scale was set consistently with the bounding box. Both *pointing* and *delimiting* 2D AMs were oriented overlaying them on the principal plane of the bounding box, whose normal vector most approximates the user's viewing direction.

As for the color, we defined eleven "basic color categories" using Berlin and Kay's process of categorizing basic color terms by their seven-stage evolution process [61]. Moreover, as done in [49], we excluded gray and black because they rendered poorly on an OST display. Of the remaining nine colors, we converted the position of each centroid from the Munsell color system to sRGB coordinates. Therefore, our selected colors for the experiments were white (RGB = 255, 255, 255), green (61, 145, 89), blue (22, 128, 162), yellow (237, 192, 44), red (174, 42, 50), purple (123, 87, 142), orange (226, 127, 45), brown (140, 94, 46), and pink (214, 124, 130). All AMs are designed with an opacity set as alpha = 1 (opaque). This choice ensured that all colors were sufficiently visible with the maximum HoloLens graphic output.

Regarding the animation, in addition to choosing a static AM, we selected two of the most frequently used animations to catch the user's attention. The "blinking" effect as done in [52], [55] and the "wipe" one [56].

3.4 Participants

We recruited 45 unpaid participants (11 females, 20-34 years old, mean=24.7, SD=3.01) from our university and local companies. They were 7 bachelor's and 24 master's degree students in engineering, 8 Ph.D. students in mechanical engineering, and 6 employed engineers. All participants had normal or corrected-to-normal vision and no color vision defects. On a 7-point Likert scale, the mean familiarity level with AR was 3.29 (SD=2.10, Min=1, Max=7). While wearing the HoloLens, participants could keep their eyeglasses on. The study required no specific previous experience from users. The experiment lasted on average 45 min for each participant, including the final questionnaire.

3.5 Procedure

A balanced Latin Square was used to establish the order of the 10 components to be localized by each user. The choice of AM properties through the developed AR GUI for each component can be summarized as follows (Fig. 5):

- Users were informed about the component to localize through a photograph displayed in the AR GUI.
- Users could try all the proposed AM shapes rendered in the Unity Default Material Shader without animation, and then select the one they considered most suitable to localize the component.
- Users confirmed the selection, and then the GUI allowed them to choose the color. Users could try the selected AM shape with all the available colors and select the one they considered most suitable. The experimenter recommended users choose the color pragmatically instead of their preferred one.
- Users confirmed the selection, and then the GUI allowed them to choose the animation. Users tested the selected AM shape and color with all the available animations and selected the condition they considered most suitable.

Users' motivations about the selected AM properties were collected at the end of each choice.

3.6 Results and Discussion

We collected data regarding the frequency with which AM properties were selected by the interviewed participants for each component.

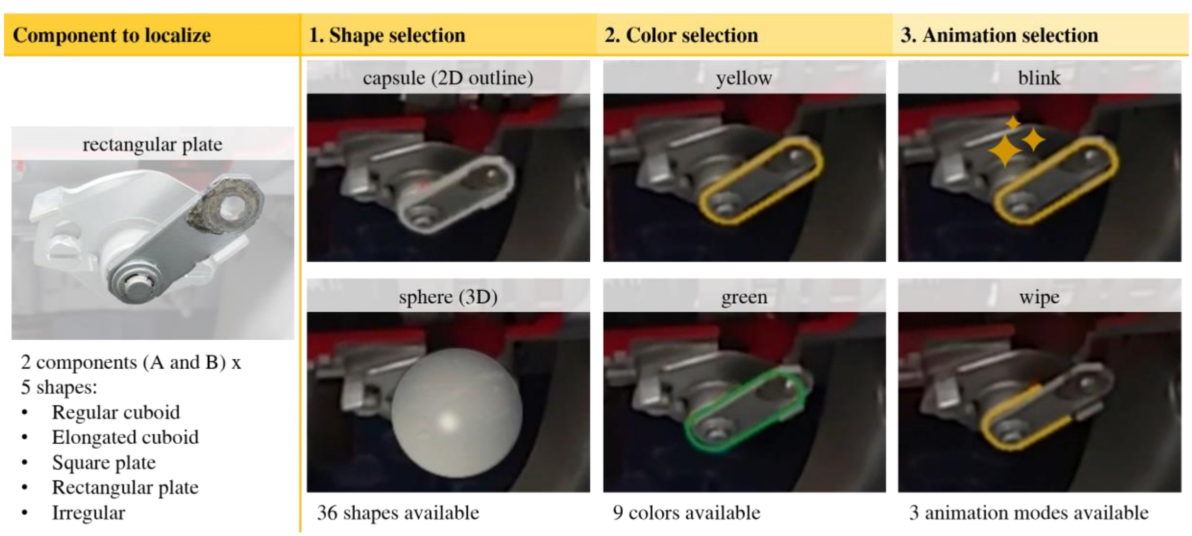


Fig. 5. Procedure for US1: users chose the AM properties for 10 components of 5 different shape categories. They first selected the shape of the AMs among 36 possible available shapes; then, for the selected AM shape, users chose the color and the animation. We reported only some examples of the possible choices.

		Regular cuboid A	Regular cuboid B	Rectang. plate A	Rectang. plate B	Square plate A	Square plate B	Elongated cuboid A	Elongated cuboid B	Irregular A	Irregular B
3D	Cuboid		2%		2%			2%		2%	
	Semisphere					7%				7%	2%
	Pyramid									2%	
	Tube	11%	2%		2%		4%	29%	22%	7%	2%
	Curved cylinder								2%		4%
	Cylindrical arrow	4%	2%	4%	2%	9%		9%			9%
	Sphere	4%	2%			2%				4%	7%
	Cone									2%	
	Cylinder	62%	13%			4%	7%	20%	22%	29%	
	Capsule		2%	9%				11%	9%		
	Toroid		7%			7%	22%				2%
	Prismatic arrow		11%	2%		16%		4%		4%	16%
2D outline	Circle		11%	4%			51%	4%	2%	13%	11%
	Square	2%			18%			2%			
	Right triangle										
	Hexagon		16%			16%	4%			9%	
	Equilateral triangle				2%					2%	
	Pointed arrow		2%	4%		2%					11%
	Capsule			53%	7%			9%	27%		
	Rounded square	7%			24%			2%			
	Pentagon		2%							2%	2%
	Rhombus										4%
	Arrow		4%	2%			2%		2%		11%
	Arc										4%
2D filled	Circle					2%	9%	2%			
	Square				13%					2%	
	Right triangle										
	Hexagon		13%			24%				7%	
	Equilateral triangle									4%	
	Pointed arrow	4%	2%	2%	7%	2%					
	Capsule			18%	4%			2%	11%		
	Rounded square				16%			2%			
	Pentagon					2%					
	Rhombus										
	Arrow	4%	7%		2%	7%			2%	2%	7%
	Arc										7%

0													65%

Fig. 6. Frequency with which an AM shape was chosen by participants for each component. The heatmap chart helps show the trends among AM shape proposals; a white box represents no proposals, and a darker color indicates a high number of proposals.

3.6.1 Shape

As regards the shape, a mapping of the frequency of AM shapes and the corresponding components can be seen in Fig. 6. We observed that no users proposed a unique AM for every component. On average, they chose 7.3 (SD = 1.5) different AMs. We further inquired if, based on user preference, it is possible to propose specific AM shapes based on the five categories of component shapes.

For the *regular cuboid* category, before the experiment, we hypothesized that a 3D sphere, cuboid, or cylinder would have been the most preferred AM because this kind of component covers the space uniformly in the three directions. The most chosen AM was the *3D cylinder* selected by 62% of users for component A. We observed a greater uncertainty for component B probably because, due to its small dimensions (a nut), it tends to appear as a point with a reduced effect of the component shape. However, the *3D cylinder* turns out to be one of the highest rated proposals also for component B. For both the components of this category, users motivated their choice saying that the 3D cylinder approximated well the shape of the component. This consideration can be generalized to other industrial components in this category since the cylinder is a common shape of components in machines (e.g., shafts, pins, screws) compared to other shapes.

For the *elongated cuboid* category, before the experiment, we hypothesized that 3D shapes with one dimension much greater than the other two (such as cylinder, capsule, or cuboid) would have been the most preferred. For component A, the *3D tube* (29%) and the *3D cylinder* (20%) were revealed to be a proposal with a very high agreement compared to all the other shapes. For component B, there is a higher uncertainty. We can make the same considerations done for the *regular cuboid* category. When the component is thin, like component B (a thin lever), its shape tends to appear as a line, thus, reducing the effect of the component shape. Users motivated their choice by saying that the 3D shapes (cylinder and tube) enclosed the component well with the advantage for the tube that allows seeing the component inside it.

For the *rectangular plate* and *square plate* categories, we made the same hypothesis before the experiment. Indeed, we assumed that 2D outline shapes would have been the most preferred because they can clearly highlight the component without occluding it. For the *rectangular plate* component A, the *2D capsule* is a proposal with a very high agreement, especially for the outline shape (53%) compared to the filled one (18%). In the same way, for the *rectangular plate* component B, there is a high agreement for the *2D square* shape with both segmented (31% overall, 18% for the outline one and 13% for the filled one) and rounded edges (40% overall, 24% for the outline one and 16% for the filled one). For the *square plate* component A, the *2D hexagon* was revealed to be a proposal with a very high agreement both for the outline shape (16%) and the filled one (24%). Whereas for the *square plate* component B, there is a very high agreement for the *2D outline circle* (51%). For both the categories of components, users motivated their choice by saying that, considering the small thickness for this kind of components, a 3D model is not justified. Then, among the 2D models, they selected the shape more representative of the boundary of the component preferring the outline version because it did not occlude the component. These results are in accordance with our hypotheses, further enriched with the novel insight about the shape of the AM. We considered these results generalizable to other industrial components belonging to this category.

For the *irregular* category of components, before the experiment, we hypothesized that uniform shapes like the 3D sphere or cuboid would have been the most preferred because they could englobe the component independent of its specific form. For both components A and B, we found a high disagreement among the proposals. For component A, *3D cylinder* (29%) and *2D outline circle* (13%) are the most preferred. For component B, *3D cylindrical arrow* (16%), *2D outline circle* (11%), *2D outline prismatic arrow* (11%), and *2D outline cylindrical arrow* (11%) are the most preferred. Users said it was difficult to find a suitable AM for this kind of components. Based on the survey results, we considered that they could not easily be generalizable and further research is needed before providing a guideline for this kind of components.

3.6.2 Color

From the data analysis about color, we observed that five users proposed the same color independent of the component shape, and in four cases, it was yellow. Fig. 7 shows data collected about the frequency of AM colors. The most chosen color is yellow for all the component categories: on average, it was chosen by 34% of users, with a maximum frequency of 44% for the *regular cuboid* component B and a minimum frequency of 22% for the *rectangular plate* component A. The other colors received lower preferences, with green (on average 13%), red (13%), and blue (12%) more selected than all the others. This result is consistent with numerous studies in the literature [49], [50] in which yellow and green are favored in perception with OST devices because perform more consistently and reliably compared to other generally recognizable colors. Another possible reason for the choice of yellow is that it contrasts well with most of the engine components in the proposed case study.

3.6.3 Animation

Fig. 8 shows data collected about the frequency of AM animations. The most chosen animation is the blinking effect. It was preferred for all the component categories except for the elongated cuboid

	Regular cuboid		Rectangular plate		Square plate		Elongated cuboid		Irregular	
	A	B	A	B	A	B	A	B	A	B
Orange	13%	9%	20%	4%	7%	16%	7%	9%	9%	4%
Blue	9%	9%	9%	16%	7%	11%	13%	16%	18%	16%
Yellow	36%	44%	22%	40%	40%	24%	31%	36%	29%	36%
Brown	4%	2%	11%	7%	4%		2%	7%	2%	
Pink	2%		11%		2%	2%		2%	2%	2%
Red	11%	9%	11%	9%	16%	18%	20%	9%	16%	11%
Green	7%	18%	7%	18%	13%	18%	13%	9%	9%	18%
Purple	9%	2%	2%		2%		4%	7%	7%	7%
White	9%	7%	7%	7%	9%	11%	9%	7%	9%	7%

0 … 65%

Fig. 7. Frequency with which an AM color was chosen by participants for each component.

component A, for which the user preferred a static AM but with a very similar frequency. On average, the blinking effect was chosen by 47% of users, followed by the static one (30%), and the wipe one (23%). According to user feedback, the blinking effect captures more attention than the other proposals. Furthermore, blinking 3D AMs compared to the static ones allow the component to be visible during the blinking. Finally, users who preferred a static AM judged that an animation was unnecessary, especially for large-scale components.

3.7 Design Guidelines

Based on the results of US 1, we formulated the following recommendations for the design of AMs:

- For a component with a regular cuboid bounding box (*regular*), use a 3D cylinder.
- For a component with an elongated cuboid bounding box (*elongated*), use a 3D tube or cylinder.
- For a component with a plate bounding box (*plate*), use a 2D AM with a shape that replicates the boundary of the component.
- Independent of the component shape, use yellow AMs with a blinking animation.

The previous guidelines apply only to components that cover the bounding box uniformly (V>0.2), whereas for more irregular shapes, further research is needed.

4 User Study 2: Validation of the Guidelines

To validate the results obtained in US 1, we designed a second user study (US 2) in which we performed an objective evaluation. We compared AMs designed according to the guidelines derived from US 1 with an AM designed according to what is evident in the literature and what is available using commercial AR authoring platforms.

4.1 Design and Methodology

We conducted a within-subject user study with two independent variables: component shape (*regular*, *elongated*, and *plate*) and AM shape (*baseline* and *optimized*). Thus, we tested six experimental conditions. For each one, we made four replications selecting four different components for each of the three component shapes, for a total of 12 components. The case study was the same engine of US 1.

The AM shape used as a baseline was a 3D prismatic arrow widely used in the literature for this kind of task. Furthermore, 3D prismatic arrows are recurrent cues used in commercial AR authoring tools such as Microsoft Dynamics 365 Guides and Microsoft Dynamics 365 Remote Assist. According to our guidelines, the shape of optimized AMs was tailored to the component shape. We proposed the *3D cylinder* for the *regular* category, the *3D tube* for the *elongated* category, and a *2D outline* shape that follows the boundary of the component for the *plate* category. Based on the results of US 1, we used yellow (RGB = 237, 192, 44) for the proposed AMs and animated

	Regular cuboid		Rectangular plate		Square plate		Elongated cuboid		Irregular	
	A	B	A	B	A	B	A	B	A	B
Wipe	24%	16%	24%	20%	20%	18%	27%	24%	33%	22%
Blink	49%	58%	56%	42%	49%	47%	36%	47%	36%	53%
None	27%	27%	20%	38%	31%	36%	38%	29%	31%	24%

0 … 65%

Fig. 8. Frequency with which an AM animation was chosen by participants for each component.

them with a blinking effect. 3D arrows were rendered in yellow too, thus applying the results of US1 because there are no clear recommended colors in the literature. On the contrary, for the animation, we found that most of the interfaces use static AMs. Then, we found more appropriate to use a static 3D arrow as a baseline. The choice of the baseline properties is further confirmed by an analysis of commercial AR authoring tools, such as Microsoft Dynamics 365 Remote Assist, where it is possible to change the color of the AM but not associate an animation. As for the position, orientation, and scale of our AM proposals, we set the Unity transform properties as done in the US 1.

We compared the performance (localization time and recognition accuracy) and user experience (ease of localization, clarity of localization, and enjoyment) in the localization task performed using baseline and optimized AMs for the three component shapes. Before the experiment, we formulated the following hypotheses:

H1. The localization time with optimized AMs is significantly lower than the baseline for all the component shapes.

H2. The recognition accuracy with optimized AMs is significantly higher than the baseline for all the component shapes.

H3. The user experience with optimized AMs is significantly higher than the baseline for all the component shapes.

4.2 Participants

From our university and local companies, we recruited 24 unpaid participants (8 females, 21-32 years old, mean=24.1, SD=2.40) different from the participants of US 1. They were 7 bachelor's and 11 master's degree students in engineering, 5 Ph.D. students in mechanical engineering, and 1 employed engineer. All participants had normal or corrected-to-normal vision and no color vision defects. On a 7-point Likert scale, the mean familiarity level with AR was 3.21 (SD=2.20, Min=1, Max=7). While wearing the HoloLens, participants could keep their eyeglasses on. The study required no specific previous experience from users. The experiment lasted on average 25 min for each participant.

4.3 Procedure

The setup was the same as the US 1. We implemented a second GUI, placed above the engine so that it is always accessible to the user without obstructing the area designated for the localization task with the HoloLens. The experiment consisted of localizing each of the 12 components as quickly as possible through the AR information shown. Each component had to be identified by the optimized AM and the baseline following a sequence of 24 trials (2 AM shapes x 3 component shapes x 4 replications of components). We designed a randomly generated predetermined sequence for each participant. The localization task for each component can be summarized as follows:

- Users pressed the "Start" button on the GUI to start the localization task.
- Users identified the component exploiting the AM.
- Users pressed the "Finish" button to confirm that they had identified the component.

During the test, the localization time for each AM was automatically acquired by the application and stored in an online spreadsheet. The localization time was measured since users pressed the "Start" button to begin the localization task to when they pressed the “Finish” button to end the task. As part of the task, users were required to touch the localized component physically, enabling the experimenter to record any potential errors encountered manually. At the end of the experiment, users were asked to fill out a subjective questionnaire in terms of ease of localization, clarity of localization, and enjoyment. This questionnaire consisted of rating on a 7-point Likert scale (1 = strongly disagree, 7 = strongly agree) respectively the following 3 statements: (i) “It allows me to localize the component easily”; (ii) “It allows me to localize the component without ambiguity/confusion with respect to nearby components”; (iii) “I enjoyed in using it to localize a component.” Users rated both the optimized and the baseline AMs for each component category.

4.4 Results

All data recorded from each participant (localization time, recognition accuracy, and user experience rating) were classified as matched continuous variables because data were obtained for each user under all the experimental conditions. The Shapiro–Wilk normality test, AS R94 algorithm, revealed that all the original data did not follow a normal distribution. Therefore, for each data, the Wilcoxon ranks-sum test was used as nonparametric test to compare 2 samples. Table 3 summarizes the results obtained from the statistical analysis.

As for the localization time, we did not find a statistically significant difference between the proposed design of AMs and the baseline for all the experimental conditions. Then, we rejected H1.

As for the recognition accuracy, we measured the error rate for each experimental condition as:

$$ER\% = \frac{\text{N. errors}}{(\text{N. participants}) * (\text{N. components})} * 100 \qquad (1)$$

We found a statistically significant error rate reduction with the proposed design compared to the baseline for all the experimental conditions. Fig. 9 shows data collected considering the errors for all the four replications of each condition. These results allowed us to confirm H2.

As to the subjective measurements, we collected data about the ease of localization, clarity of localization, and enjoyment of use. For each of these qualities, we found a statistically significant improvement in user experience with the proposed design compared to the baseline for all the experimental conditions. Fig. 10 shows the total data collected for all the four replications of each condition. These results allowed us to confirm H3.

4.5 Discussion

The results of US 2 confirmed, in terms of performance and user experience, the guidelines formulated in US 1.

As for user performance, even if we did not find a statistically significant difference in localization time, we observed a significant improvement in recognition accuracy with optimized AMs, compared to the baseline, in all the experimental conditions. The motivation is that AMs designed according to our guidelines delimit the correct component negligibly englobing other close components. On the contrary, 3D arrows point at the component, making its recognition difficult with respect to the nearby ones or those in the same line of sight. Probably, users could perform more accurately with 3D arrows if they observed the component from various viewpoints. However, this behavior would have resulted in a longer localization time. Another variable that contributed to increasing the recognition accuracy with optimized AMs is the blinking animation. It proved decisive in allowing the users to understand the right component without having the occlusion issue caused by a static AM.

The considerations derived from analyzing the results about recognition accuracy were further confirmed by evaluating the user experience. The three subjective measurements were rated significantly higher using our optimized AM with respect to the baseline for all the component shapes. Users preferred using optimized AMs because they allowed them to easily recognize the component without ambiguity with respect to others close to it.

Table 3. Results of statistical analyses for the data measured in US 2. The asterisks indicate statistically significant different conditions.

Measurements		Optimized auxiliary model vs. baseline		
		Regular	Elongated	Plate
Objective	Localization time	Z=-1.739 p=0.082	Z=-1.432 p=0.152	Z=-1.538 p=0.124
	Recognition accuracy	Z=-3.000 p<0.001*	Z=-5.000 p<0.001*	Z=-5.831 p<0.001*
Subjective	Ease of localization	Z=-3.609 p<0.001*	Z=-3.871 p<0.001*	Z=-3.927 p<0.001*
	Clarity of localization	Z=-4.321 p<0.001*	Z=-4.230 p<0.001*	Z=-4.143 p<0.001*
	Enjoyment	Z=-3.609 p<0.001*	Z=-3.964 p<0.001*	Z=-3.742 p<0.001*

Moreover, from a hedonic point of view, they stated that the optimized AMs make the task more interesting and enjoyable.

5 Overall Discussion

The results of this work allowed us to answer affirmatively to our research question: *“is it possible to design optimized auxiliary models for locating in-view not occluded components according to their shape?”* The US 1 revealed that there is not a unique recommendable shape of AM for different shapes of components to localize, whereas the use of yellow color and blinking animation can be generalized. Based on the results of US 1, we proposed guidelines for designing optimized AMs to localize in-view and not occluded components with regular shapes in complex machines. These components can be well represented by their bounding box, whose aspect ratio determines the recommended auxiliary model. The US 2 confirmed that optimized AMs lead to improved performance and user experience compared to generic 3D arrows. Though we used complex industrial equipment as a case study, our results can also apply to other industrial scenarios (e.g., electrical panels) as well as to other fields involving localization tasks where objects close to each other can be confused if localized through 3D arrows. For example, in cultural heritage applications, highlights of museum installations and descriptions can be exploited to improve visitors' knowledge [62]. At the same time, in medicine, a patient’s anatomy localization can help surgeons in prosthesis placement [63]. We can generalize our results because we defined the component shape based on a pure geometric feature, i.e., the own bounding box. This classification could also be applied to objects different from industrial components, such as architectural elements or organs.

Previous studies revealed that peripheral cueing, i.e., salient spatial cues at the relevant position, induces faster attentional shifts than central cueing, i.e., a symbolic cue like an arrow, because the latter needs additional time to interpret the symbol [64]. However, the pure localization task addressed in our study is relatively simple and rapid to accomplish. Therefore, we did not find an improvement in the

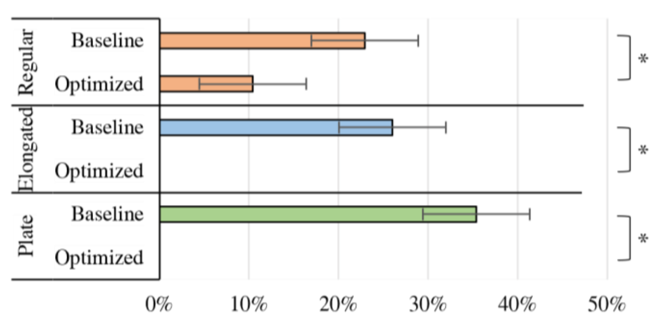


Fig. 9. Error rate for all the experimental conditions. The asterisks indicate statistically significant different conditions.

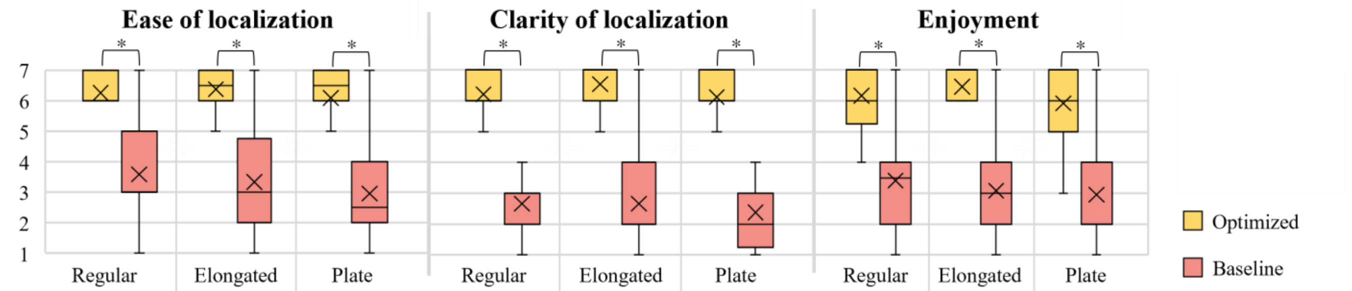


Fig. 10. Median scores for subjective measurements in terms of ease of localization, clarity of localization, and enjoyment for all the experimental conditions. The asterisks indicate statistically significant different conditions.

localization time using optimized AMs. Nevertheless, users reported that localizing components using them was easier than 3D arrows. The more relevant result of this study regards the accuracy of the localization task. The use of *delimiting* AMs with a shape geometrically similar to that of the component, implies less ambiguity in recognizing it with respect to arrows. In fact, arrows indicate a point in the space but, in complex machines, this point may be associated with various components very close to each other. Furthermore, arrows in AR interfaces are used for purposes other than localizing in-view components, e.g., as directional arrows to indicate out-of-view objects [22], [23], as indicators of navigation direction [65], or as interaction buttons [66]. Then, operators may misinterpret the information associated with the arrow.

An interesting finding of this study regards the use of animations. Though they do not provide further information for the localization task, the results of this work revealed that the blinking animation can produce some beneficial effects. First, it helps users to catch their attention towards components. Then, it is also helpful to overcome the occlusion caused by 3D AMs, resulting in a valid alternative to transparency [37], [38] and wireframe rendering [39], used in previous studies. Finally, they improve the operator's enjoyment in accomplishing procedural tasks.

The use of yellow also helps direct user attention compared to other colors. In fact, yellow contrasts very well with machine components, generally metallic, with a consequent dominance of gray and dark colors.

These results regarding animations and colors agree with [67], stating that salient attributes like movement and color can be used as peripheral cueing, thus improving attention guidance. Furthermore, our study also revealed that colored and animated AMs enhance operators' enjoyment. This result is very important from the perspective of Industry 5.0, which places the well-being of industrial workers at the center of the production process [68].

6 Future Work and Limitations

The design guidelines provided in this work can be implemented in AR authoring tools to propose AMs to convey the localization information automatically. From the CAD model of the component or its point cloud, it is possible to determine its bounding box and calculate the shape factors r, k, and V. Based on their values, the tool could display the AM in the authoring interface with the position, orientation, and scale automatically set according to the bounding box. This kind of tool would be very powerful in reducing the effort in the authoring of AR interfaces. In this work, we limited to characterizing the shape of a component through its bounding box. In future work, it could be further possible to replace the bounding box by proposing optimized AMs according to the actual shape of a component. In fact, using deep learning, a subset of Artificial Intelligence techniques, it would be possible to improve the accuracy and robustness of tracking methods (such as point cloud tracking [30]) for the detection and identification of objects [69]. Deep learning techniques have already been proposed for localization tasks, but previous works have limited to use rectangular bounding boxes as AR cues [70], [71]. These could be replaced through optimized AMs exploiting the results of our work and through future studies where the preference for a wider range of components could be collected. In fact, through semantic segmentation, future authoring tools would be able to identify almost precise pixel-level boundaries of objects [69] and then propose the optimized AM for that component.

We limited this study to the localization of in-view and not occluded objects. In fact, many previous works have already addressed how to draw user attention to out-of-view objects, e.g., using 3D arrows [22], [44], pulsing 3D halos [22], or a 2D bar [72]. They could be easily integrated with AMs designed with our guidelines: until the object is out-of-view, one of these visualization methods can be used to direct user attention; then, when the object is in-view, an optimized AM can be used to locate it exactly. However, there is still the possibility that, though the object is in-view, it could be hidden by other objects. In this case, particular rendering techniques, such as alpha blending [73], [74], must be applied to the AMs to allow users to understand to which component it refers. An alternative solution to localize components in such blind areas could be using exogenous cues such as a side-by-side 3D model or a virtual mirror, as proposed in [75]. Further research is then needed to understand how to design AMs in case of occluded components.

7 Conclusion

We conducted two user studies to determine if optimized AMs can be designed for the localization of in-view not occluded components in complex industrial equipment. The first study revealed a dependence between the shape of AMs proposed by users and that of the component to localize, defined through its bounding box. This result allowed us to propose four design guidelines that were positively validated through a second user study. We found that yellow blinking AMs, whose shape is designed according to our guidelines, improve recognition accuracy and user experience compared to generic 3D arrows. The findings of our studies allowed us to propose our design guidelines for the authoring of future AR technical documentation.

Supplemental Materials

A video of the procedure for US1 and US2 is available at https://youtu.be/_ZwvJM00GIw.

Acknowledgments

This work was supported by the Italian Ministry of University and Research under the Programme "Department of Excellence" Legge 232/2016 (Grant No. CUP - D93C23000100001). Finally, the authors would like to acknowledge also all the people involved in the experiment for their time spent in this research.

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