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Evaluation of Augmented Reality Tools for the provision of Tower Air Traffic Control using An Ecological Interface Design

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One of the major problems faced by the growth of air traffic in the last decade is the limited capacity of the runway especially during low visibility procedures (LVP) due to fog and bad weather. To solve this issue, the project "Resilient Synthetic Vision for Advanced Control Tower Air Navigation Service Provision" (RETINA) project, a two-years exploratory research project, under SESAR2020 program, proposes to use new Synthetic Vision (SV) and Augmented Reality (AR) technologies for the tower controllers to allow them to conduct safe operations under any Meteorological Conditions while maintaining a high runway throughput, equal to good visibility. In this paper we introduce the Ecological Interface Design (EID) as a methodology to investigate the potential and applicability of SV tools and Virtual/Augmented Reality (V/AR) display techniques for the Air Traffic Control (ATC) service provision by the airport control tower. We explain how the EID framework can be used in RETINA, we experiment the framework on a suitable airport and we provide the EID results comparing normal and LVP conditions with operations using RETINA technologies.

I. Introduction

During the last decade, different tools have been developed to ease the work of air traffic controllers (ATCOs) at airports and to safely handle the increase in traffic such as time based separation, safety nets or the reduction of the minimum separation. But in low visibility condition, the safe minimum separation is increased and the airport capacity is reduced. Low visibility procedures exist to support Low Visibility Operations at Aerodromes when either surface visibility is sufficiently low to prejudice safe ground movement without additional procedural controls or the prevailing cloudbase is sufficiently low to preclude pilots obtaining the required visual reference to continue to landing. Surface visibility may be relatively good but the tower visual control room may be in cloud or fog and ATCOs keep Low visibility operations on place when the conditions on the terrain are different and the separation between aircraft can be reduced.

To tackle this problem, the project Resilient Synthetic Vision for Advanced Control Tower Air Navigation Service Provision (RETINA) proposes the use augmented reality technologies[1]. It evaluates and challenges the different innovative solutions that can be applied in a control tower by using the Ecological Interface Design (EID).

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II. EID Framework

A. Introduction

Ecological Interface Design is a theoretical framework for designing human-machine interfaces in complex, real-time and dynamic environments. EID differs from User-Centred Design (UCD) insofar it focuses on the work domain rather than on the end user requests, "ecological" is referred to an interface that has been designed to reflect the constraints of the work environment in a way that is perceptually available to the people who use it. Simply put, the users are able to take effective actions with the interface, understanding how those actions will move them towards their interface.

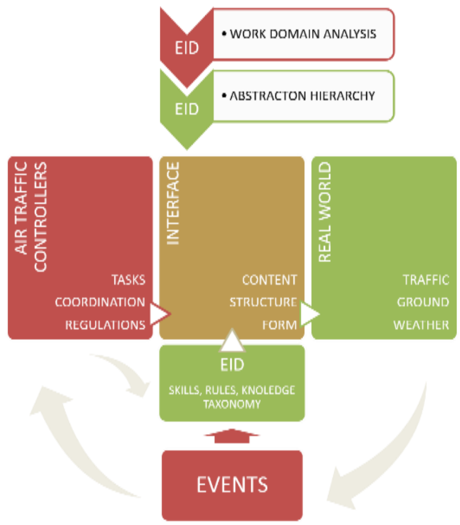

Figure 1: EID Framework

B. EID Structure

The goal of EID is to make constraints and complex relationships in the work environment perceptually evident (e.g. visible, audible) to the user. This allows more of users' cognitive resources to be devoted to higher cognitive processes such as problem solving and decision making. EID is based on three key concepts from cognitive engineering research:

- the Work Domain Analysis,
- the Abstraction Hierarchy (AH) and
- the Skills, Rules, Knowledge (SRK) framework.

By reducing mental workload and supporting knowledge-based reasoning, EID aims to improve user performance and the overall system reliability for both anticipated and unanticipated events in a complex system.

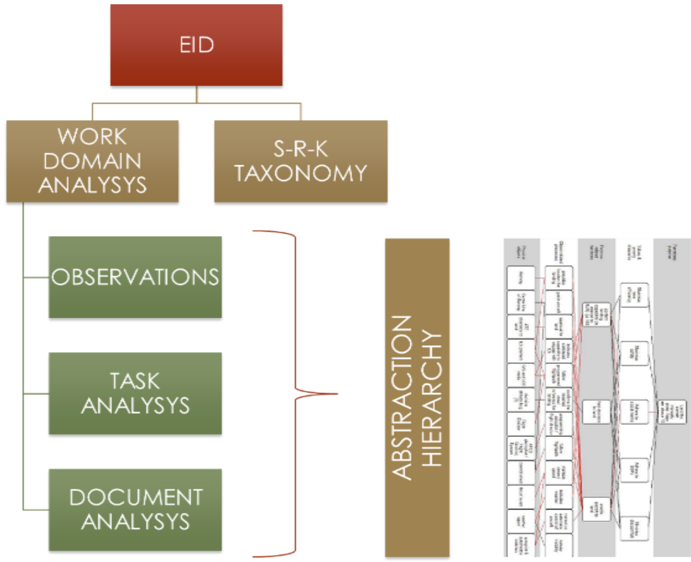

Figure 2: EID Structure

1) *Abstraction Hierarchy*

The Abstraction Hierarchy (AH) is a 5-level functional decomposition used for modelling the work environment, or more commonly referred to as the work domain, for complex sociotechnical systems **Error! Reference source not found.**[1]. In the EID framework, the AH is used to determine what kinds of information should be displayed on the system interface and how the information should be arranged. The AH describes a system at different levels of abstraction using how and why relationships. Moving down the model levels answers how certain elements in the system are achieved, whereas moving up reveals why certain elements exist. Elements at highest level of the model define the purposes and goals of the system. Elements at the lowest levels of the model indicate and describe the physical components (i.e. equipment) of the system. The how and why relationships are shown on the AH as means-ends links. An AH is typically developed following a systematic approach known as a Work Domain Analysis [3]. It is not uncommon for a Work Domain Analysis to yield multiple AH models; each examining the system at a different level of physical detail defined using another model called the Part-Whole Hierarchy **Error! Reference source not found.**.

Each level in the AH is a complete but unique description of the work domain.

2) *Functional Purpose*

The Functional Purpose (FP) level describes the goals and purposes of the system. An AH typically includes more than one system goal such that the goals conflict or complement each other **Error! Reference source not found.**. The relationships between the goals indicate potential trade-offs and constraints within the work domain of the system. For example, the goals of a refrigerator might be to cool food to a certain temperature while using a minimal amount of electricity.

3) *Abstract Function*

The Abstract Function (AF) level describes the underlying laws and principles that govern the goals of the system. These may be empirical laws in a physical system, judicial laws in a social system, or even economic principles in a commercial system. In general, the laws and principles focus on things that need to be conserved or that flow through the system such as mass **Error! Reference source not found.**. The operation of the refrigerator (as a heat pump) is governed by the second law of thermodynamics.

4) *Generalised Function*

The Generalised Function (GF) level explains the processes involved in the laws and principles found at the AF level, i.e. how each abstract function is achieved. Causal relationships exist between the elements found at the GF level. The refrigeration cycle in a refrigerator involves pumping heat from an area of low temperature (source) into an area of higher temperature (sink).

5) *Physical Function*

The Physical Function (PFn) level reveals the physical components or equipment associated with the processes identified at the GF level. The capabilities and limitations of the components such as maximum capacity are also usually noted in the AH **Error! Reference source not found.**. A refrigerator may consist of heat exchange pipes and a gas compressor that can exert a certain maximum pressure on the cooling medium.

6) *Physical Form*

The Physical Form (PFo) level describes the condition, location, and physical appearance of the components shown at the PFn level. In the refrigerator example, the heat exchange pipes and the gas compressor are arranged in a specific manner, basically illustrating the location of the components. Physical characteristics may include things as colour, dimensions, and shape.

7) *Skill, Rule And Knowledge Based Taxonomy*

The Skills, Rules, Knowledge (SRK) framework or SRK taxonomy defines three types of behaviour or psychological processes present in operator information processing [3]. The SRK framework was developed by Rasmussen **Error! Reference source not found.** to help designers combine information requirements for a system and aspects of human cognition. In EID, the SRK framework is used to determine how information should be displayed to take advantage of human perception and psychomotor abilities **Error! Reference source not found.**. By supporting skill- and rule-based behaviours in familiar tasks, more cognitive resources may be devoted to knowledge-based behaviours, which are important for managing unanticipated events. The three categories essentially describe the possible ways in which information, for example, from a human-machine interface is extracted and understood:

a) *Skill-based level*

A skill-based behaviour represents a type of behaviour that requires very little or no conscious control to perform or execute an action once an intention is formed; also known as a sensorimotor behaviour. Performance is smooth, automated, and consists of highly integrated patterns of behaviour in most skill-based control [7]. For example, bicycle riding is considered a skill-based behaviour in which very little attention is required for control once the skill is acquired. This automaticity allows operators to free up cognitive resources, which can then be used for higher cognitive functions like problem solving [8].

b) *Rule-based level*

A rule-based behaviour is characterised by the use of rules and procedures to select a course of action in a familiar work situation [7]. The rules can be a set of instructions acquired by the operator through experience or given by supervisors and former operators.

Operators are not required to know the underlying principles of a system, to perform a rule-based control. For example, hospitals have highly-proceduralised instructions for fire emergencies. Therefore, when one sees a fire, one can follow the necessary steps to ensure the safety of the patients without any knowledge of fire behaviour.

c) *Knowledge-based level*

A knowledge-based behaviour represents a more advanced level of reasoning [9]. This type of control must be employed when the situation is novel and unexpected. Operators are required to know the fundamental principles and laws by which the system is governed. Since operators need to form explicit goals based on their current analysis of the system, cognitive workload is typically greater than when using skill- or rule-based behaviours.

d) *Skill-Based Behavior*

At the skill-based level, the behaviour is regulated by the lowest level of conscious involvement and is characterized by highly routinized and automated activities. In fact, skill-based mode refers to "the smooth execution of highly practiced, largely physical actions in which there is virtually no conscious monitoring".

- High Automated processes involving long term memory (procedural)
- Low Executive control (i.e. low attention and working memory)
- No Decision-making (resolution of conflicts and error detection)
- No Problem solving

e) *Rule-Based Behaviour*

Rule-based behaviour is also activated in familiar work situations, but it is distinguished from skill-based behaviour, as "it requires some degrees of conscious involvement and attention. Situation assessment leads to recognition of which procedures apply to particular familiar situations".

- Less automated processes and long term memory (procedural) than Skill level
- More executive control (i.e. more attention and working memory) than Skill level
- No Decision-making (resolution of conflicts and error detection)
- No Problem solving

f) *Knowledge-Based Behaviour*

When faced with unfamiliar situations, where no solutions are already available, it is necessary to move to the knowledge-based level of behaviour. At this level, the User "carries out a task in an almost completely conscious manner. This would occur in a situation where a beginner is performing the task (e.g. a trainee at the beginning of its training) or where an expert is facing with a completely novel situation. In either such cases, the User would have to exert considerable mental effort to assess the situation, and his or her responses are likely to be slow. Also, after each control action, the User would need to review its effect before taking further action, which would probably further slow-down the responses to the situation".

- No automated processes and long term (procedural) memory
- Executive control (high attention and working memory)
- Decision-making (resolution of conflicts and error detection)
- Problem solving

g) *The use of CONSTRAINTS*

EID is also about exposing "constraints" in order to facilitate the operator job and move complex cognitive behaviors toward simpler cognitive behaviors (K –> R –> S)

III. METHODOLOGY

As mentioned above, EID is a theoretical framework that can be used to tackle the problem of HMI design for the control of highly complex systems. For the purpose of the RETINA project, i.e. investigating the use of Augmented Reality technologies in the Airport Control Tower environment, the S-R-K taxonomy was applied to the control tower working environment in order to study how the introduction of a properly designed HMI based on AR technology would impact the ATC operations. Moreover, the methodology was used as input to design the Augmented Reality overlays, which are synthetic graphical elements used to expose/move relevant information onto the outside of the window view.

To sum up, theS-R-K taxonomy is used in the framework of the RETINA project to design a newly conceived AR based HMI in order to:

- Expose/move relevant information onto the outside of the window view
- Make constraints visually perceivable
- Increase controllers' situation awareness

It is assumed that, in low visibility conditions, the movement of relevant information from the traditional head-down interface to the out-of-the-tower head-up view will lead to less limitations, with a positive impact in terms of:

- Increased capacity
- Increased efficiency
- Increased safety.

This assumption was validated in the framework of the RETINA project and the present paper does not cover the validation activities and results.

A. RETINA EID Workflow

The S-R-K taxonomy applied to the control tower tasks should provide different results according to the current working condition (visibility, traffic), Tower Equipment based on surveillance equipment, e.g. Advanced –Surface Movement Ground Control Surveillance (A-SMGCS),) and procedures.

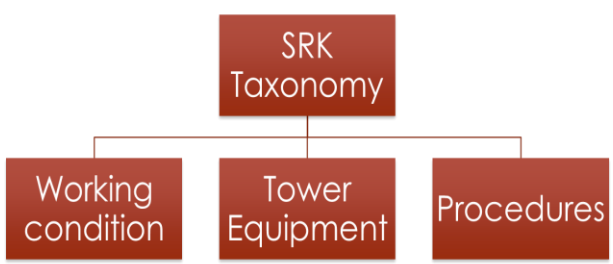

Figure 2 Tower Task S-R-K

The following table provides an example of S-R-K taxonomy for Ground departure ATCO on normal visibility and standard procedures, and it shows different controllers tasks and their assessment based on the S-R-K Taxonomy. It is worth to notice that the assessment made to categorize a task or a subtask as S-R-K based behaviour is intrinsically affected by a certain degree of fuzziness. This is due to the fact that each subject may behave in a slightly different way when performing an assigned task/subtask in specific conditions.

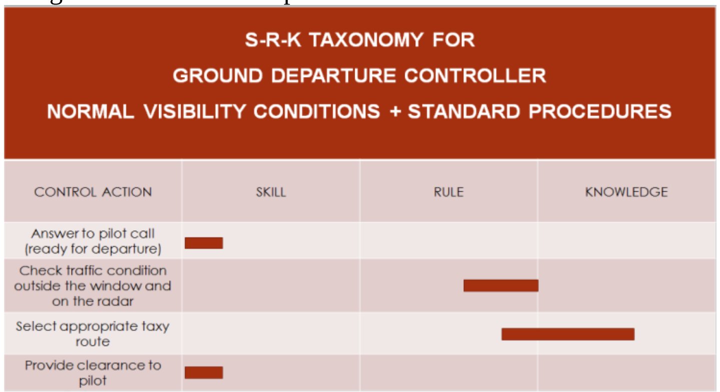

Figure 3: S-R-K for Ground ATCOs

The workflow for SRK taxonomy applied to RETINA is described below:

- Identify Case Studies (i.e. working environments to be analysed in specific conditions).
- Perform S-R-K Taxonomy for each selected case study.
- Identify shifts in cognitive behaviour, due to the entry in force of LVP “Improve” cognitive behaviour by exposing constraints, moving information.
- Design overlays.
- Remove limitations.

B. Airport selection

In order to be eligible for the implementation phase, an airport shall meet some basic requirements useful for a first application of V/ARTT. These requirements are related to the equipment, to the airport lay-out, to the traffic and to the ATC procedures.

In order to provide V/ARTT with the position and identification of aircraft on the manoeuvring area and in the Aerodrome Traffic Zone, the airport shall be equipped by Primary and Secondary Surveillance Radar (PSR/SSR) and by Surface Movement Radar (SMR). PSR/SSR provide position and identification of aircraft in the Aerodrome Traffic Zone, i.e. a specific traffic volume around the airport that includes final segments of instrumental procedures and visual circuit patter. The SMR provides the position of all the traffic (aircraft and vehicles) in the manoeuvring area that includes runway and taxiway.

Airports with a moderate complexity in term of layout have some strong benefit for a first implementation of V/ARTT. First of all the manoeuvring area is easy to model and the restrictions of the Low Visibility Procedure results in a more effective manner. Moreover, as first implementation step, a too big manoeuvring area could be confusing and dispersive.

The airport shall be able to support low visibility conditions and ATC Low Visibility Procedures shall be implemented. This is very important in order to show the benefits provided by the V/ARTT when the visibility conditions are critical. CAT II/III approach and LVTO (Low Visibility Take Off Operations) shall be available; this means in terms of equipment that the airport shall be ILS CAT 3B equipped.

Finally, it is important that specific procedures for the apron management are available and implemented. Typically, such procedures are based on slots and times displayed on video and often implicate ATCO head down operations. The integration of such information in the V/ARTT has several benefits.

Resuming, in order being eligible for the implementation phase, an airport shall have at least the following features:

- Primary Surveillance Radar and Secondary Surveillance Rada (PSR/SSR) equipped;
- Surface Movement Radar (SMR) equipped;
- Low Visibility Procedures able to manage more than one aircraft at the same time implemented;
- ILS CAT 3B equipped;
- Moderate complexity (one runway, several taxiway, more than one apron)
- Moderate traffic: volume of 200/300 movement per day;
- Apron Management Procedures available;

Guglielmo Marconi International Airport in Bologna (LIPE) has been chosen as reference scenario for the implementation phase. Bologna Airport meets all the requirements mentioned above moreover the Control Tower is quite big in order to easily host future real time experiments

IV. Results and Discussion

A. EID Analysis

1) Working condition and environment

The S-R-K analysis will be focused on the following working conditions applied to Bologna airport:

- VMC scenario: visibility equal or greater than 5km and ceiling equal or greater than 1500ft (VFR flights available).
- IMC visibility
    - CONDITION 1: there is no condition for the visual flights but visibility condition 1 still hold. Visibility condition 1 is the visibility sufficient for the pilot to taxi and to avoid collision with other traffic on taxiways and at intersections by visual reference, and for personnel of control units to exercise control over all traffic on the basis of visual surveillance. IMC visibility
    - CONDITION 2: Visibility condition 2 is the Visibility sufficient for the pilot to taxi and to avoid collision with other traffic on taxiways and at intersections by visual reference, but insufficient for personnel of control units to exercise control over all traffic on the basis of visual surveillance. IMC visibility
    - CONDITION 3: Visibility sufficient for the pilot to taxi but insufficient for the pilot to avoid collision with other traffic on taxiways and at intersections by visual reference, and insufficient for personnel of control units to exercise control over all traffic on the basis of visual surveillance. For taxiing, this is normally taken as visibilities equivalent to an RVR of less than 400 m but more than 75 m.

2) S-R-K Analysis

This section reports a SRK analysis of the controller tasks for each selected use cases. This analysis is performed in 3 steps:

- categorization of controller tasks in each visibility condition;
- categorization of controller tasks by excluding the limitation based on visibility condition;
- categorization of controller tasks by excluding the limitation based on visibility condition and using RETINA technologies.

In order to perform the analysis, each controller task is split in the related subtasks. For each of them, all the dimensions of the controller cognitive process – namely automation, executive control, decision-making and problem solving - are qualitatively evaluated assigning a ranking value i.e. high, medium, low for the level of automation and executive control, and yes/no for the use of decision-making and problem solving.

TASK GND 1 – Issue ATC clearance:				
1. Active electronic strip on FDP	high	low	No	No
2. check SID: ATC have to check if SID is congruent to rwy in use and other restrictions (if present)	medium	medium	No	No
3. assign initial level: Local procedure request to assign 5000ft to every flight (rules)	high	low	No	No
4. ATC clearance: Transmit ATV clearance – hear-back – confirmation of the correct receipt of the authorization (standard phraseology)	high	medium	No	No

Figure 5: Example of Subtask analysis

Figure 5 reads as follow: the task “issue ATC clearance” has a high level of automation and requires to apply rules increasing attention and the use of working memory.

The task GND 1 is evaluated between the category skill based behaviour, rule based behaviour.

The table in figure 6 reports the S-R-K analysis of the controller tasks for each scenario: a dedicated colour coding is used to identify each scenario in order to perform a comparison of the S-R-K categorization of the used scenarios. Figure 7 reports a qualitative analysis of the controller tasks using retina overlays which are able to provide the controller with all the data previously described. Figure 8 shows the analysis assuming the use of Retina overlays with no LVP limitation or regulations (as operating in VMC).

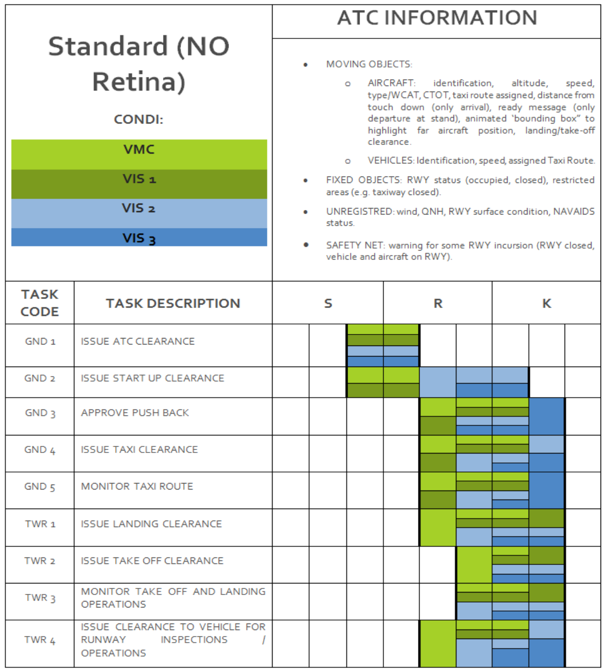

Figure 6: S-R-K on standard operations

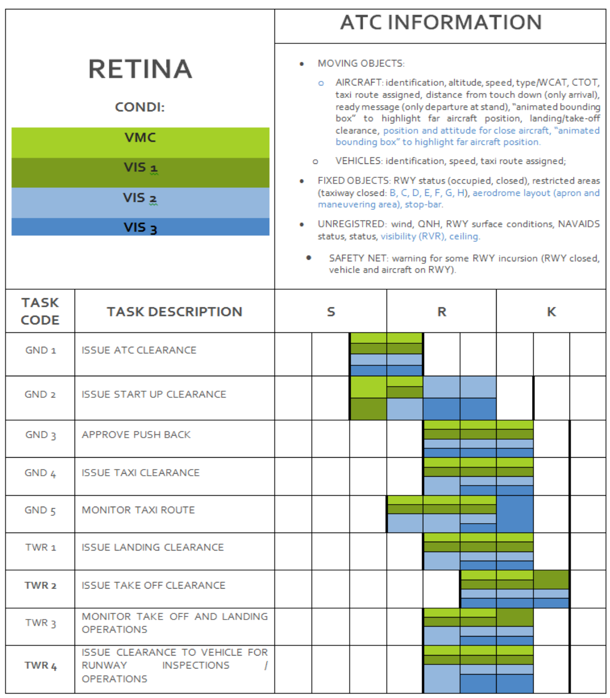

Figure 7: S-R-K in all conditions

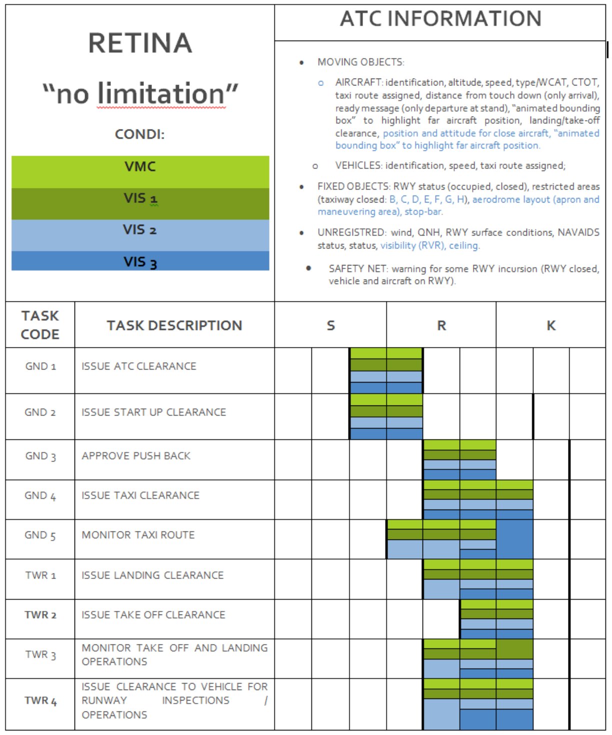

Figure 8: S-R-K in all condition using RETINA

The following tasks require further considerations:

- Task GND 2, ISSUE START UP CLEARANCE: Workload decreases because there are no more restrictions (as CTOT) due to airport capacity .
- Task GND 4, ISSUE TAXI CLEARANCE:It is supposed that there are no restrictions, no closed taxiway, there is no obligation to use the stopbar, the controller's workload in conditions of visibility 3 can be considered the same as in VMC.
- Task TWR 2, ISSUE TAKE OFF CLEARANCE: It is assumed that there are no controller's visual limits: this simplifies the observation of aerial overflights of LLZ. This limit remains necessary for operation in Class II / III, in order to protect the ILS sensitive areas.

B. Results Discussion

The S-R-K analysis has been used to evaluate the controller tasks and the possible impact that could have the use of Retina tools. Each controller tasks has been divided in subtasks and, for each of them, the S-R-K "dimensions" (i.e. automation, executive control, problem solving and decision making) have been evaluated in each scenario. The knowledge-based behaviour is the most "consuming" in term of resources for a controller performing his/her tasks: low visibility scenarios require a greater use of the "knowledge" compared to the VMC scenario. This is typically mitigated via the application of restrictions (number of taxiways available in low viability, aerodrome capacity, etc.) that shifts the behaviour to the rules-based behaviour field. Considering the tables reported above, it is easy to see that the use of Retina tools potentially mitigates the shift to the knowledge-based behaviour due to low visibility condition (Fig. 7 vs Fig.8). The analysis shows the suppression of all restrictions in low visibility conditions as a what if analysis, i.e. what happens absurdly if we remove all retractions applicable in low visibility. Also in this context it is easy to see that RETINA tools make it possible to balance the shift to the knowledge-based behaviour.

V. Conclusion

In this paper, we applied the Ecological Interface (EID) design to the control tower tasks to evaluate the use of the Resilient Synthetic Vision and augmented reality for Advanced Control Tower, the results show that introducing those technologies balance the shift to the knowledge-based behaviour which means safe operations at high capacity, even in Low visibility conditions leading to the achievement of resilient all weather conditions operations. All the results concerning the SRK taxonomy were collected based on task analysis thus they are subjective and inherently affected by a certain degree of fuzziness nevertheless the concept was subsequently assessed through HIL validation reporting positive results which are not covered in the present paper.

Acknowledgments

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