Enhancing Naval Enterprise Readiness through Augmented Reality Knowledge Extraction

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ABSTRACT

The newest wave of Naval aircraft carriers are implementing novel systems that require fewer Sailors to man, with the goal of improving readiness and reducing operating costs. These new, unique systems have led to an increase in required training hours for Sailors. To address this gap, recent developments in Naval training have included the use of emerging technologies, such as augmented reality (AR), to support high velocity learning. However, what is still lacking is the ability to transition this emerging technology to on-the-job training in the form of job performance aids (JPAs). Due to the reduced-crew environments of the new Ford-class carriers, expert Sailors have less time available to mentor and coach journeymen Sailors. The present paper discusses the application of AR for the extraction of expert maintainer knowledge, allowing the Navy to capture expert maintainers' hard-earned expertise and then distribute this knowledge for life-long Naval enterprise use. By using AR, the knowledge extraction process can become semi-automated, standardized and repeatable, thus ensuring quality content is consistently obtained. Further, the use of a head mounted display (HMD), like the HoloLens 1, allows expert maintainers to capture knowledge while being hands-free to complete their tasks. With AR, content can be captured from a first-person perspective, providing ultimate operational support to Sailors. This allows journeymen maintainers to "take experts with them," as they need support in their work, long after those experts have retired. This paper discusses the development of such an AR application, evaluation of the AR tool onboard the CVN 78 with Machine Control Monitoring System (MCMS) maintenance technicians, and concludes with a summary of initial lessons learned, and immediate future directions.

ABOUT THE AUTHORS

Dr. Victoria L. Claypoole is a Research Associate with Design Interactive, Inc. With previous experience at the Air Force Research Lab and her current work with the United States Navy, Dr. Claypoole's research interest lies at the intersection of increasing warfighter readiness and advancing scientific knowledge. Currently, her work is centered on leveraging emerging technology to develop next-generation training and operational support for the warfighter. She received a Ph.D. in Human Factors and Cognitive Psychology and a Master's in Modeling and Simulation from the University of Central Florida.

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INTRODUCTION

Recent advancements in emerging technology have made their way into the United States Military. Most prominently, the Navy's newest aircraft carrier, the USS Gerald R. Ford (CVN 78) has leveraged this new technology to improve readiness and reduce operating costs by building smarter systems that require fewer Sailors to man. Formalized Naval training has even started to adopt the usage of emerging technologies. For example, Augmented (AR) and Virtual Reality (VR) are used to train Sailors pier-side within the new high velocity learning environment, Carrier-Advanced Reconfigurable Training System (C-ARTS). C-ARTS allows Sailors to complete refresher training, prepare for qualifications, and even receive entry-level training all within a reconfigurable trailer that uses the latest advancements in extended reality (XR) and other emerging technologies, like 3D printing.

While emerging technology has been exercised to improve training, reduce manning requirements, and build "smarter ships," the utilization of emerging technology has not been extended to the capture and dissemination of subject matter expertise. The military, like many commercial organizations, is experiencing a new and daunting challenge – how to maintain institutional knowledge and experience during the Silver Tsunami, as Baby Boomers exit the workforce. Even more so, reduced-crew carriers, like the CVN 78, have significantly fewer expert Sailors onboard resulting in the crew having less time to spend on things like training their replacements before they are transitioned. Thus, there is a need to capture and disseminate subject matter expertise before expert Sailors leave their station – either through retirement or transition. Previous research has used knowledge elicitation, or KE, methodologies to capture subject matter expert (SME) knowledge; however, innovation has failed organizations, as though there have been huge volumes of research in the area of KE (e.g., Cooke, 1994; Shadbolt & Smart, 2015), it has not resulted in any widely adopted tools to support knowledge extraction. The present article briefly discusses the limitations of traditional KE methodologies, describes a new approach utilizing emerging technology, and presents an initial evaluation of the feasibility of this new, innovative approach.

AUGMENTED REALITY FOR KNOWLEDGE ELICITATION

Limitations on Current Knowledge Elicitation Methodologies

KE has been described as the process of collecting human sources of knowledge (Cooke, 1994). Previous research has identified dozens of methodologies for KE, but they are typically grouped in three categories: observations and interviews, process tracing, and conceptual techniques (for a full review, see: Cooke, 1994; Shadbolt & Smart, 2015). Most of these methodologies result in analyses that are left to researcher interpretation – meaning, that the outcome of the KE process is a researcher's interpretation of the information provided by the expert. The expert is often left out of this interpretation and thus results can become skewed. Further, KE methodologies have been noted to capture primarily explicit (i.e., easily articulated) and implicit (i.e., procedural or conditional) knowledge. A major limitation to these researcher-led approaches is that tacit knowledge, which is made up of mental models, perceptions, insights, assumptions, values, beliefs, etc., is seldom captured as it is difficult for experts to articulate (Cooke, 1994). Additionally, most experts utilize their own set of heuristics while they troubleshoot issues or complete procedures. Heuristics are traditionally regarded as an important aspect of expert knowledge. For instance, based on established heuristics, a SME may try one troubleshooting test over another due to an availability heuristic (e.g., the test has led to more successful outcomes relative to the other tests). These expert heuristics are often difficult to capture in standard knowledge elicitation methodologies as heuristics are considered to be tacit knowledge and thus difficult to articulate. Heuristics are also most critical for procedural knowledge, and previous research has indicated that acquiring procedures from text, such as the outcome from traditional knowledge elicitation sessions, can suffer due to reading comprehension errors and a lack of prior declaration knowledge acquisition (Bovair & Kieras, 1991)

Another criticism of historical KE approaches is that it is difficult to make the process repeatable/reliable and free from bias, as even with a semi-structured cognitive interview, questions asked to each expert often vary based on responses provided and the inclinations of the researcher asking the questions. In addition, these methodologies are time consuming, rely on having a researcher-in-the-loop, and can be difficult to analyze and interpret.

The use of computer-aided systems for KE is not novel (e.g., Cooke, 1994). However, what is still lacking is the ability to capture tacit knowledge with these solutions. The KE approach herein describes leveraging emerging AR technology to guide and capture tacit knowledge. From a theoretical perspective, AR most aligns with constructivist learning theory (Dunleavy & Dede, 2014; Martín-Gutiérrez et al., 2010), as it positions experts within a real-world physical and social context. A key component of this theory relevant to AR is that contextually relevant environments embedded within the learning experience increase the overall quality of learning and memory (Maclellan & Soden 2004). Abstracting this to KE, if AR can afford greater learning experiences through contextualization, it should also afford greater memory recall when completing tasks during a KE session. Further, a plethora of previous research has indicated that memory recall is enhanced when it is retrieved in the same manner in which it was encoded (e.g., conditions, locations, etc.), indicating that memory can be context-dependent (Godden & Baddeley, 1975). Taken together, past research suggests that memory recall and stimulation should be greater when activated in contextually relevant environments. Thus, utilizing AR HMD devices to elicit knowledge in operationally relevant environments and allowing experts to physically complete tasks as they provide their expertise should result in capturing a greater breadth of knowledge, including hard to verbalize tacit knowledge.

A Novel Approach Leveraging Emerging Technology

To overcome limitations of current KE methodologies, a new KE approach was developed in conjunction with several government agencies and industry partners, including the Office of Naval Research (ONR), PEO Carriers, Naval Education and Training Command (NETC), Cape Henry Associates, CACI, and Huntington Ingalls Inc. The approach, termed EXpertise TRansfer, Analytics, and Content Tagging (EXTRACT), couples venerated experts with web-based and emerging AR technologies to prime memory and aid in recall. The EXTRACT approach has three main components: A web portal to provide a familiar and easy-to-use medium via which experts can share their explicit and implicit knowledge, innovative AR technology to provide a contextually primed mechanism to further expound upon information elicited in the web portal, and, also within the AR environment, utilization of deep probing questions aimed at fostering critical thinking and associated capture of tacit knowledge. Each of these three components provide a unique contribution to the novel KE approach described in more detail below.

In previous KE methodologies, web portals have been used that incorporate cognitive interviews to capture episodic knowledge associated with specific cases (Moody, Will, & Blanton, 1996). While valuable, the case-specific knowledge garnered from this approach would not be expected to broadly generalize. There is a need to create a more generalizable approach which elicits knowledge appropriate for training across the proficiency continuum from novice to expert (Dreyfus, 2004). The approach taken within EXTRACT is to couple the *Cognitive Process Dimensions* (i.e., remembering, understanding, applying, analyzing, evaluating) and *Knowledge Dimensions* (i.e., factual, conceptual, procedural, metacognitive) of Bloom's revised taxonomy (Krathwohl, 2002) with *Progressive Deepening Probes* from the Critical Decision Method (CDM; Sieck & Klein, 2007) and, in turn, couple these tools with contextually relevant AR environments to prime memory and elicit knowledge across the proficiency continuum. The result is a knowledge base that can be used to get the right information to the right technician at the right time and in the right form.

The EXTRACT web portal is used to present a template structured according to Bloom's *Cognitive Processes* and *Knowledge Dimensions*, where experts can easily fill out information regarding troubleshooting symptoms, sensory cue descriptions (e.g., which senses they use to detect symptoms and a description of this detection process), tests used to narrow down to a root cause, and steps within those tests – to name a few. These template structures allow experts to quickly and easily convey their explicit (knowing what) and implicit (knowing how) expertise in a manner that is structured and organized according to how people progress from novice to expert. Templates have been used in previous research as an effective method in which to provide narrative storytelling to transfer knowledge (Davenport, 2011). When these templates are used for KE and coupled with immersive AR technology and progressive deepening to elicit tacit knowledge, the result is a mechanism via which to prime all dimensions of knowledge in a structured and organized manner that is repeatable across KE sessions.

A core component of the EXTRACT approach is the use of emerging technologies, specifically AR, to aid in the capture of critical domain knowledge. AR can provide a contextually rich and relevant environment, which establishes the sensory conditions needed to prime experts and enables them to communicate tacit knowledge that underlies their expertise. The AR device selected for the EXTRACT approach was the Microsoft HoloLens 1. This device is a head-mounted display (HMD), which allows experts to be completely hands-free as they use the system. This functionality was critical to the success of the novel approach described herein. The HMD allows experts to complete the KE process while simultaneously completing the real-world tasks they are asked to knowledge capture. The information elicited in the web portal is presented in the HMD to reactivate memory, ultimately enhancing recall by guiding and prompting experts throughout the immersive AR elicitation process. By using the HMD, experts can capture videos of completing a mechanical procedure while they respond to EXTRACT system Bloom's-based prompts and CDM-based progressive deepening probes. The structured templates, prompts, and progressive deepening probes were designed to extract explicit (i.e., can be easily described), implicit (i.e., procedural and conditional), and tacit (i.e., difficult to articulate) knowledge regarding a task domain. Experts are provided guidance on when to capture media and what type of media is best for the content they are describing (e.g., static content for pictures, dynamic content for videos). By allowing experts to capture their own, first-person media, they have the opportunity to provide supplemental information, beyond that captured in the EXTRACT web portal, on critical cues they actually attend to and components they work with during task performance. Further, the elicited media can be later used as a job performance aid (JPA) for operational support. Capturing first-hand media of what experts see and do, coupled with their explanations, allows for subject matter expertise to be used within JPAs, thereby enabling journeymen Sailors to take their "experts" with them as they receive AR-based operational support.

The EXTRACT approach for knowledge elicitation was initially designed for maintenance-related troubleshooting processes as a starting point from which to evaluate the effectiveness of utilizing AR for KE. However, the templates, prompts, and probing questions were designed to be easily modified for other domain areas. The template-like structure of the web portal, combined with the contextualized guidance within AR, provides a consistent organization for KE across domains. The process is repeatable from start to finish, as every user encounters the same experience, and allows for standardization between KE sessions, which ultimately results in the capability to disseminate consistent support derived from the KE sessions. This contextualized and semi-automated elicitation approach promises to far surpass traditional researcher-in-the-loop KE methods (Shadbolt & Smart, 2015).

EXTRACT Approach for Knowledge Elicitation: Detailed Description

To complete the EXTRACT process for KE, experts first access the web portal application. The web portal allows experts to fill out templates regarding the problem summary, needed reference materials, associated symptoms with supporting sensory system descriptors, and steps required to complete the troubleshooting process. Experts are also presented with a brief series of deep probing questions reflective of Bloom's Cognitive Processes along Knowledge Dimensions (e.g., Kairasian et al., 2001). Once complete, the responses to the web portal are then exported to the AR device, specifically, the Microsoft HoloLens 1. Once experts don their AR device, they are instructed to travel to the location of the first symptom of their troubleshooting process. From there, the system represents the information typed in the web portal as a mechanism to further prime and activate memory. The AR system guides the expert through additional steps of the KE process, including guidance on when to capture media (i.e., pictures, videos, and audio clips) and what type of media is best for the present content. While donning the AR headset, experts complete a thorough review of the information they entered in the web portal, are instructed to physically complete each troubleshooting step in the relevant environment (i.e., allowing time to travel in-between physical locations, if necessary), and are afforded opportunities to provide additional information (e.g., symptoms, steps, etc.) in the AR device. Experts capture a plethora of media (i.e., pictures, videos, and audio notes) regarding the troubleshooting process and respond to another series of progressive deepening probes that are better suited for video or audio response, as opposed to the written text responses obtained in the web portal. These deep probing questions, presented in an operationally relevant environment, are aimed at capturing tacit knowledge and ask experts to think critically about relevance of cues, consequences of errors, and other factors previously associated with tacit knowledge. Once complete, the AR responses are exported back to the web portal where experts have a final opportunity to review their responses and captured media before moving on to the publishing process (not described here). *Figure 1* presents a pictorial representation of the KE process experts move through as they complete the EXTRACT approach.

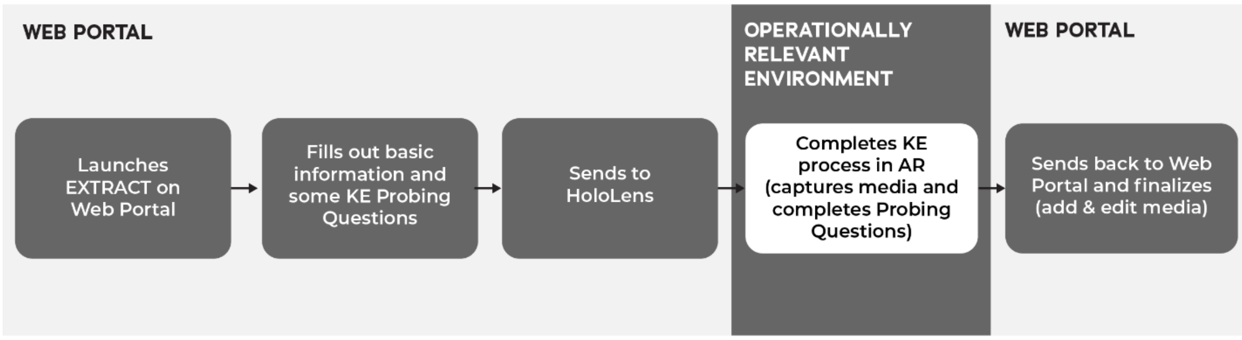

Figure 1. Basic User Flow for the EXTRACT Approach to Knowledge Elicitation

EVALUATION OF AUGMENTED REALITY FOR KNOWLEDGE ELICITATION

The purpose of the present evaluation was to evaluate the efficacy of utilizing AR for KE, particularly, in an operationally relevant environment to demonstrate the feasibility of such an approach with the overarching goal of enhancing Naval readiness. This novel approach was examined within the maintenance domain. Overall, three evaluations were conducted. First, Sailor inputs to the KE tool were examined to determine the extent of knowledge captured (e.g., explicit, implicit, tacit). Sailor inputs were compared against available technical manuals to establish the efficacy of the novel KE approach. Second, an operational evaluation was conducted to analyze the increase in effectiveness related to currently available systems and how well this approach, and the technology it leverages, functioned within the constraints onboard ship. Finally, perceived usability of the system was assessed to evaluate user acceptance and adoption of the system. The following sections describe the selected population and use case, detail the methodology employed, and describe results of the evaluations.

Population and Use Case

A unique challenge for the USS Gerald R. Ford is that with fewer Sailors to man dozens of new systems, journeymen Sailors may be underprepared and lack operational support via on-the-job training for systems with which they have little-to-no previous experience or training. The overarching purpose of EXTRACT is to capture and disseminate critical expert knowledge so that journeymen have access to the right support at the right time – even when subject matter experts (SMEs) are unavailable to provide assistance. Thus, to demonstrate the feasibility of the novel AR-based KE approach, the following parameters were identified to aid in the selection of a use case that would be strategic for both the evaluation of the EXTRACT approach and for the CVN 78 due to current manning and SME access:

1. The system should be unique to the CVN 78, so as to provide the most value for Naval applications.
2. The system should have only minimal expert Sailors who are able to provide operational support.
3. The system should be receptive to AR technology (e.g., require hands-on maintenance).
4. The system should have troubleshooting processes or procedures that are either unique, complex, or rarely performed so that captured knowledge can be used by journeymen Sailors in future operations (i.e., a procedure in which a junior Sailor *would* require operational support).

Based on these parameters, the Machinery Control Monitoring System (MCMS) was selected as the system in which to evaluate the EXTRACT approach. MCMS is operated by the Combat Systems (CS) Department; specifically, CS 5 – Combat Data System and Tactical Networks Division. MCMS is the Command's largest and most complex system (Thompson, 2018). MCMS controls over 5,600 field devices from a centralized computer system. Some of the systems controlled by MCMS include all the air conditioning systems throughout the ship (Lessig, 2014). MCMS allows for a modern approach to system monitoring; instead of individual Sailors monitoring individual systems, MCMS can monitor and control thousands of systems and sub-systems, which allows for fewer required Sailors to man the CVN 78. This automated approach provides an opportunity to reduce crews and increase readiness. However, as this system is novel and expansive, Sailors receive little-to-no formalized training in A and C schools (training programs specific to a Sailor's intended role, or rating) specifically on MCMS systems prior to boarding the CVN 78. Thus, there is a potential operational support gap for these Sailors.

MCMS is a new system for Naval aircraft carriers and is currently only found on the CVN 78, though it is also being installed on the USS John F. Kennedy (CVN 79). At the time MCMS was selected, only two Sailors were considered to be maintenance experts with the system onboard the CVN 78. MCMS operation requires frequent troubleshooting and repair of numerous sub-systems, many of which are mechanical in nature and require Sailors to perform hands-on maintenance. Two use cases were identified within the MCMS system for use with the EXTRACT approach for knowledge elicitation. Both use cases require complex troubleshooting and hands-on testing of equipment. They also require hands-on maintenance, while also involving elements of computer-supported tasking. Further, failure of either use case is considered to be a Class A mishap and has serious consequences for the readiness of the aircraft carrier. Thus, it is imperative to keep both use cases functional and operational, resulting in high criticality of troubleshooting and repair for these use cases. The identified use cases are strategic for both the evaluation of the EXTRACT approach and for MCMS Sailors, and, if successful, will provide an opportunity to leverage emerging technology for capturing and disseminating expert knowledge and providing operational support.

Method

All three evaluations were conducted onboard the CVN 78. Specifically, the evaluations were held in the MCMS Control Room. This room is the central area for MCMS Sailors and contains an admin computer station that allows maintainers to check the status of every single field device housed within the ship. Though MCMS maintainers engage in troubleshooting and repair procedures throughout the aircraft carrier, the control room is the central hub where trouble calls are received, and troubleshooting is initiated.

MCMS has two expert maintainers available to provide operational support and mentorship to junior maintainers. Both expert Sailors participated in the present evaluations. First, both Sailors were asked to independently complete the EXTRACT approach for knowledge elicitation. Sailors first entered information into the web portal. Within the web portal, the Sailors were asked to provide symptoms related to one of the aforementioned use cases and describe the tests performed to narrow down the root cause. They also were asked a series of probing questions related to the troubleshooting process. Once the web portal interface was completed Sailors moved on to the AR interface. Once they donned the AR headset, the system represented the information Sailors had entered in the web portal and guided them through the immersive KE process (e.g., capturing supplemental media and providing expert advice during task performance). Additional progressive deepening probes aimed at tacit knowledge capture were also presented. From start to finish, completion time for EXTRACT was less than two hours for both the web portal and AR components, per Sailor. Once the Sailors completed EXTRACT KE approach, the System Usability Scale (SUS; Brooke, 1996) and qualitative interview questions were administered. A description of these instruments is provided below. The surveys took each Sailor approximately 30 minutes to complete. Thus, the total time for all three evaluations was approximately 2.5 hours per Sailor.

System Usability Scale (SUS)

The SUS (Brooke, 1996) was developed out of a need to provide user experience researchers with a quick and valid approach for assessing usability. The SUS has been reported in thousands of studies and has proved to be a commonly used and reliable questionnaire for end-of-test subjective evaluations of usability (Finstad, 2006; Lewis, 2006; Bangor, Kortum, & Miller, 2009). The SUS allows researchers to quickly and easily collect subjective ratings of product usability via a 10-item, Likert-style questionnaire with five-point anchors ranging from 'Strongly Agree' to 'Strongly Disagree' (Bangor et al., 2009). Scoring of the SUS yields a usability score in the range of 0–100 where scores over 80 indicate excellent usability of a system (Bangor et al., 2009).

Qualitative Interview Questionnaire

The qualitative interview questionnaire reported in the present evaluations was developed by the researchers to assess the feasibility of operational implementation of EXTRACT and to determine overall user attitudes towards the system. Questions such as "*What was the level of difficulty for capturing media in the headset?*"; "*What did you think of the knowledge capture process?*"; and "*Did you experience any issues with the system's audio or visual presentations?*" were verbally asked to both Sailors, individually. See Table 1 for a full list of questions presented.

Results and Discussion

Knowledge Capture

Analysis of the web portal responses indicated that, as expected, expert maintainers primarily provided explicit and implicit knowledge in this form factor. The stepwise information for tests and test-steps were reflective of the technical manual for MCMS sub-systems. However, in response to the web portal probing questions, experts provided information that far surpassed the technical manual. They provided detailed responses for categories such as alternative approaches, tips and tricks, and basic facts. These detailed responses provide an opportunity to transfer this expertise into a JPA for operational support or formalized, proficiency-based training that is supportive of journeymen Sailors across the proficiency continuum. Thus, by analyzing the web portal responses of the EXTRACT system, the results indicate that explicit and implicit knowledge can be captured and disseminated in such a way that all Sailors are supported, similar to that of previous KE methodologies but with generalizable knowledge captured via the Bloom's-based prompts and CDM-based progressive deepening probes.

Table 1. Qualitative Interview Questions Provided during Evaluations

Qualitative Interview Questions
How comfortable are you in wearing the headset?
What would be the max length of time you would want to spend in the headset, in one sitting?
How easily could you hear the system's prompts and narrations?
How easily could you see the system's visuals?
Did you experience any issues with the system's audio or visual presentations?
What was the level of difficulty for capturing media in the headset?
How well could this system be used for daily operations?
What did you think of the knowledge capture process?
Were you able to provide sufficient detail about the troubleshooting process you completed?
Did you experience any constraints while using the system?
What is your current process for sharing expertise and providing operational support?
Do you have any available systems similar to the one you just used?
Do you feel as if the current system provides a value add to your organization?

Analyses of the AR system component responses indicated that a combination of explicit, implicit, and tacit knowledge was captured in this form factor. For example, when completing questions related to symptoms, Sailors were asked to not only capture media of these symptoms, but also to explain how they detected the symptoms and discuss the relevancy, criticality, and consequences associated with the symptoms. Sailor responses to these symptom-related prompts revealed a plethora of knowledge that was not available in technical manuals and wasn't initially provided in the web portal. Thus, by providing experts the opportunity to express their expertise in an operationally relevant environment, allowing them to capture their own first-person media, and prompting them with thought-provoking progressive deepening questions specifically targeted at tacit knowledge, a wealth of information was elicited. For example, when completing this process, Sailors provided details, such as tricks and tips garnered over the years, that were not found in the technical manual for the selected use case (i.e., MCMS). Whereas, in general, SME tacit knowledge cannot be reproduced or shared easily, this evaluation preliminarily indicated that the EXTRACT approach to KE was effective in capturing SME tacit knowledge (e.g., insight, intuition, judgment, etc.), which is typically only revealed through practice in a particular context. Further, many instances of Sailors describing their preferred approach to conducting tests or completing steps provided significant supplemental implicit knowledge that will support journeymen Sailors on their path to mastery.

Successful elicitation of tacit knowledge via the EXTRACT approach is largely credited to the AR-interface and guidance provided by the system. Without allowing experts to complete the knowledge capture process in AR in their operationally relevant environment and without guiding and prompting them throughout, only explicit and implicit knowledge would have been captured – as evidenced by the web portal responses. It is clear that leveraging emerging technology, such as AR, in a scientifically grounded approach as demonstrated by the templates, prompts, and probing questions can advance KE methodologies and improve Naval readiness. Further, the EXTRACT approach provides a consistent and repeatable methodology for capturing expertise, which will allow the resulting operational support to be standardized for all Sailors. Therefore, when journeymen Sailors use resulting JPAs, they will consume the same experience with each use. This provides a significant advancement over previous KE methodologies (e.g., researcher-led), the results of which were not reproducible or standardized. Instead, the approach detailed herein allows journeymen Sailors to take their "experts" with them – they can consume first-person media from their SME, just as if that expert were guiding them in person. By having access to JPAs developed by the EXTRACT approach, journeymen Sailors are receiving expert-led instruction, formulated by a pedagogically sound model, which assists them as they complete critical procedures, resulting in improved readiness and efficiency.

Operational Evaluation

An operational evaluation was conducted to better understand any increases in effectiveness relative to traditional methods of sharing expertise and to determine the feasibility of utilizing AR devices in ship-based environments. As aforementioned, the evaluations occurred within the MCMS Control Room. This room is several decks below the main deck, relatively quiet (though there are high levels of white noise from the air conditioner required to keep the room below 60 degrees), and slightly less bright than a standard office environment. Overall, Sailors indicated that they could easily perceive both the auditory and visual elements of the AR system presented via the AR device (Microsoft Hololens 1). They were able to hear the instructions and guidance effortlessly and the visual menu system was easy to detect and interact with. Further, the cold environment of the Control Room (an operational requirement, as it is used to store and operate network equipment) ensured that the HoloLens 1 had no risk of overheating. Overall, the AR-based KE system was operationally suited for this environment and Sailors experienced no difficulties in its use, demonstrating the feasibility of an AR device for knowledge capture in the ship-based environment.

Though the parameters for an ideal use case included the use of "hands-on" maintenance, MCMS also deals heavily with network systems that require computer-based tasks; the selected use cases included elements of both "hands-on" maintenance and computer-based tasking. Therefore, to examine extensibility of AR for knowledge capture, qualitative interview questions inquired about Sailors' experience both overall and specifically with computer-centered task steps. This allowed for the examination of receptivity of using the EXTRACT approach with computer-based tasks. Sailors reported no difficulty interacting with the computer system while wearing the AR headset and could easily complete the tasks asked of them (e.g., capturing pictures and videos of their computer-based tasks). Thus, the present evaluation provides preliminary evidence that AR is receptive to capturing knowledge of computer-based tasks. This result demonstrates the extensibility of the EXTRACT approach; AR can be used to capture mechanical as well as computer-based knowledge. The latter is particularly important for representing captured expertise via an AR-based JPA. Journeymen Sailors should experience no difficulty performing computer-based tasks while receiving operational support from an AR device. However, this anticipated result should be further explored in future evaluations as previous research has demonstrated a lack of suitability for formalized training of computer-based tasks in AR mediums (Van Krevelen & Poelman, 2010).

Another operational constraint faced by MCMS Sailors is the amount of travel they must complete throughout the ship to troubleshoot and repair issues that arise. The MCMS system is critical and interfaces with every aspect of the ship. Because of this, MCMS related sub-systems are found on almost every deck of the CVN 78. To capture their expertise related to all of the various sub-systems, Sailors need to travel between multiple decks. Sailors imagined executing this travel, and the feasibility of doing so while using EXTRACT was evaluated. Sailors indicated that they would simply carry the AR headset with them during travel, similar to the manner in which they carry tool belts, and reported perceiving no issue with carrying the headset up and down flights of stairs to access various decks. In response to how comfortable they felt in wearing the headset, neither Sailor indicated displeasure or discomfort; however, it was noted that the weight of the headset may cause fatigue after extended periods of use and that they would prefer not to wear it for longer than a consecutive 60 min. Previous pilot tests of the EXTRACT approach, and the current evaluation, did not exceed 60 min within the AR headset. However, more complicated or lengthy use cases could lead to a longer completion time for the KE session. Therefore, as headsets go through re-design periods (e.g., the Microsoft HoloLens 2 is expected to be marginally lighter than the HoloLens 1), this will be an important aspect to re-evaluate. In the short-term, the AR system has design elements that allow for pausing and resuming during the KE process. Therefore, if the weight of the hardware did instantiate physical fatigue, users could pause their experience and resume at a later time. The re-presentation of web portal content within the AR headset will afford memory recall and recognition when they return.

Finally, Sailors were asked to rate their perception of effectiveness of using the EXTRACT approach relative to currently available KE systems or processes. Sailors indicated that they do not have a formal process in place for capturing and sharing their expertise. The current mechanism is limited to on-the-job training sessions with journeymen Sailors – which is often unstructured, unstandardized, and not repeatable. They indicated that using the novel EXTRACT approach would allow them to provide journeymen Sailors with a structured, standardized experience for operational support. Further, using the AR system would allow them to immediately store new tips and tricks they learn as these new systems mature. It would provide a fast and convenient mechanism for documenting undiscovered nuances of novel systems onboard the CVN 78. Thus, the EXTRACT approach would result in an immediate increase in effectiveness for providing operational support for journeymen Sailors and capturing new expertise as it becomes available with respect to new systems.

Taken together, results of the operational evaluation indicated that AR, and EXTRACT, were suitable for the ship-based environment. No issues were experienced related to perceiving the visual and auditory augmented content. Sailors could easily complete the EXTRACT process on a variety of tasks, including computer-based tasks. Therefore, at present, there are no operational concerns with executing an AR approach for KE within ship-based environments.

System Usability.
KE tool usability was assessed via administration of the SUS (see Figure 2) and through qualitative interviews. SUS results indicated that Sailors would like to use the KE tool frequently, thought it was easy to use, and felt very confident using the system. Importantly, Sailors felt that the various functions of the KE tool were well integrated and they did not perceive inconsistency within the system. This is particularly important, as this tool has both a web portal and an AR interface. Thus, users must perceive the integration of these system components as a single, streamlined system. The results suggest that the KE tool is perceived in such a way, and that targeted end users find the system highly usable and engaging. Further, Sailors *did not* find the KE tool cumbersome or awkward to use, which is important given that Sailors had to use the AR HMD device to capture media related to their expertise. This result, combined with responses to the qualitative questionnaire, indicates that Sailors had no issue capturing media in the Microsoft HoloLens while they were completing operationally relevant tasks. Additionally, Sailors reported that the KE tool was not unnecessarily complex and they would not need assistance to use the system.

The results of the individual sub-scales of the SUS can be aggregated to calculate an overall composite score of system usability (Brooke, 1996). The results of this calculation indicated that the overall SUS score of the EXTRACT KE tool was 83.75. Scores over 80 indicate that a system has excellent perceived usability (Bangor et al., 2009). Therefore, with a score of 83.75, the KE tool has demonstrated excellent preliminary system usability with MCMS maintainers onboard the CVN 78. This delineation is particularly important to note; the KE tool demonstrated excellent usability in an operationally relevant ship-based environment with actual experts completing intended tasks as they would without researcher supervision – as opposed to sanitized controlled studies or internal tests of usability.

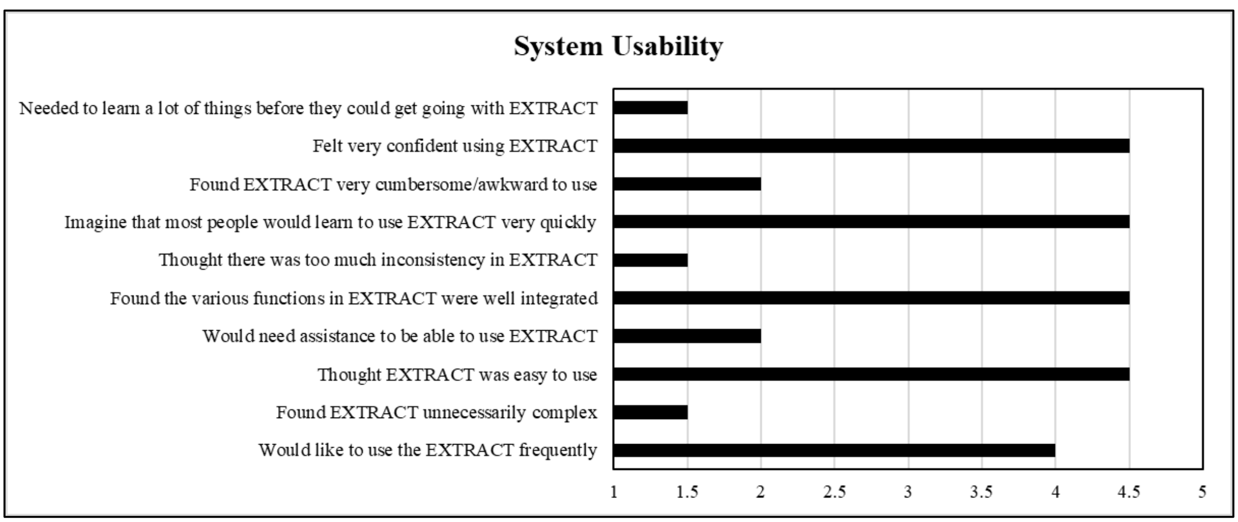

Figure 2. Average Responses to the System Usability Scale

The qualitative interviews results were similar to those of the SUS. During the qualitative interviews, expert Sailors stated that the KE tool was "*intuitive and easy to use*," "*felt like the system allowed them to leave their legacy behind*," and "*was like a digital version of their little black book*." Specifically, Sailors indicated that they did not experience difficulties with capturing media in the AR device. They found the media capture process intuitive, easy to use, and a great experience. They also indicated that they felt as if they were able to provide as much information and detail as they wanted – they did not feel as if they system imposed any limitations on their ability to effectively share their expertise. Finally, Sailors reported that they would want to use the EXTRACT KE tool to provide their junior colleagues with tips and tricks once they left their station; they felt that this system would provide a mechanism for doing so. Overall, the results of the SUS and qualitative interviews demonstrated high usability and interest, as well as evidence for user acceptance and adoption.

Lessons Learned

During the development process of the EXTRACT approach and resulting system, and as a result of the previously discussed evaluations, several 'lessons learned' were captured. First, the user interface and user interaction (UI/UX) of any AR-based knowledge capture system is critical. AR, as a whole, is still in the early design stages where standard computer design paradigms (e.g., WIMPS; Windows, Icons, Menus, and Pointers) are used in the AR space, instead of user interfaces tailored for spatial computing technologies. Specifically, the use of menus and pointers severely limits the interactions a user can have with AR systems. For the AR-based KE system, this resulted in the use of a menu system to capture and display media. For Sailors who move extensively around their immediate environment, it is crucial for these menu systems to be, at minimum, intuitive and easily accessible. Early prototype designs of the EXTRACT KE tool (also tested with Sailors), indicated that if the menu system did not follow the Sailor, the Sailor would have to move back and forth between the menu and the component they were capturing media of – or drag and reposition the menu using the "pinch and drag" interaction standard on the Microsoft HoloLens. However, the evaluation indicated that users were more naturally inclined to move towards their menu, rather than bringing the menu to them. This resulted in additional, unnecessary body and head movement; ultimately resulting in faster rates of physical fatigue and head and neck strain. Therefore, features such as 'tag-along,' where a menu follows at a close distance, and 'bill-boarding,' a behavioral UI concept where the UI is always oriented to face the user regardless of the user's position, were implemented within the system. These enhancements reduced the amount of unnecessary movement required to complete the EXTRACT approach in the ship-based environment and the amount of physical strain imposed by the AR headset and system implementation. However, as new AR devices become commercially available (e.g., Microsoft HoloLens 2), it will be imperative for all AR software developers and designers to critically examine supported UI interactions and spatial patterns to ensure applications are developed in a manner that takes advantage of the AR space while simultaneously reducing strain imposed on users. More naturalistic interactions will reduce mental and physical workload and allow for a more pleasant experience for users.

Another lesson-learned centered on the operating constraints of the selected AR device, the Microsoft HoloLens 1. With any emerging technology, it can take users time to acclimate to its use. During early tests of EXTRACT, it was reported that users had a slight learning curve with fitting the Microsoft HoloLens 1 in a comfortable position on their head. This was especially true for female Sailors, whose regulatory buns constrained the adjustable strap that held the device in place. To overcome this initial barrier, onboarding guidelines were developed to teach users how to comfortably and appropriately fit the device. Without these onboarding guidelines, users would likely incorrectly wear the headset, resulting in feelings of discomfort while completing the KE process. This 'lesson learned' is not unique to the described approach but is applicable to all AR-enabled applications. Further, developers of AR devices should examine military end-users to ensure their devices can be worn comfortably by both male and female Sailors.

Finally, results of the tacit knowledge capture indicated that both form factors of the KE tool (e.g., web and AR) were equally important for capturing expertise. Therefore, it is imperative to enable and encourage users to complete the process in the order in which it was designed. While allowing users autonomy within an application can result in higher user acceptance, constraining this freedom may result in more complete knowledge elicitation – which is ultimately of higher importance. This result demonstrated the importance of utilizing human-centered design and ensuring the resulting system minimizes constraints imposed by hardware and limits of human-information processing. By designing the system to afford memory priming and recall, users were ultimately able to provide greater detail that will serve their junior colleagues.

Overall, the results of these 'lessons learned' have led to design enhancements that are not only optimized for the Sailor, but also serve the greater intention of capturing expertise. By understanding initial limitations, and making immediate design improvements, software developers can ensure that the mechanism by which they are leveraging emerging technologies is truly user-centric and does not impose additional constraints on their users. The results here suggest that while AR is ready for prime time in applications such as knowledge capture, designers and developers alike have numerous areas for improvement to stay on the bleeding edge of these emerging technologies.

CONCLUSION AND FUTURE DIRECTIONS

Overall, results of the evaluations with MCMS Sailors onboard CVN 78 demonstrated that EXTRACT can successfully capture explicit, implicit, and tacit knowledge. Further, EXTRACT demonstrated excellent usability, which will aid in overall user acceptance and adoption. Based on these results, preliminary evidence was provided for leveraging AR technology as a viable mechanism via which to capture SME knowledge. Moreover, the aforementioned process for utilizing AR for knowledge capture was standardized, repeatable, and consistent –which greatly surpasses that of historical KE methodologies. Additionally, EXTRACT also has potential to capture the process by which SMEs troubleshoot in general. Before Sailors arrive to the Ship, they are taught a 7-step troubleshooting process in A school and a 5-step troubleshooting process in C-school. However, Master Chiefs still report needing to teach and train journeymen on how to properly troubleshoot issues. Thus, EXTRACT has potential to capture troubleshooting heuristics used by Master Chiefs and disseminate across the Fleet –providing crucial information to A and C schools on how Master Chiefs prefer their Sailors to troubleshoot issues.

To examine this new approach for knowledge capture, MCMS maintainer Sailors and sub-systems were selected as the population and use case based on a number of parameters, including consideration of unique, complex, or rarely performed procedures. However, there are many systems and sub-systems onboard CVN 78, and soon to be onboard CVN 79, that would meet these criteria. Future examinations should apply EXTRACT to other critical systems onboard the newest class of aircraft carriers to provide further evidence of its efficacy. For instance, the Plasma Arc Waste Destruction System (PAWDS) would be another suitable candidate in which to examine the efficacy of EXTRACT for KE. Like MCMS, PAWDS is a system unique to CVN 78, has very few expert maintainers, and requires hands-on maintenance (and is thus receptive to AR). PAWDS would allow EXTRACT to be examined in a different operational environment. Specifically, PAWDS is located in a more spatially constrained environment (e.g., PAWDS is only contained within three rooms instead of on every deck, like MCMS). Additionally, these rooms are not temperature controlled to stay under 60 degrees, like the MCMS Control Room, so there is potential for heat exposure, which may affect the AR devices – though further testing would be required. Thus, PAWDS would allow for another critical examination of the efficacy of AR for knowledge capture in ship-based environments.

The ultimate purpose of the EXTRACT approach is to leverage emerging technologies, like AR, to *capture* and *disseminate* subject matter expertise. The overarching goal of the present paper was to describe the process by which knowledge is captured by an AR solution and report results of a series of evaluations related to this solution. However, equally important to capturing expertise is disseminating this knowledge to journeymen Sailors to provide operational support and enhance readiness. The outcome of the EXTRACT approach and resulting system is an AR-based JPA that provides expert tips, tricks, and media components captured by the system. The representation of this content allows journeymen Sailors to "take their experts with them" as operational support when completing relevant procedures. Future work will examine the effectiveness of this JPA to determine if AR-based elicited content results in improved job performance (e.g., fewer errors, less time on task, etc.). Further, it should be determined if AR-based expert content reduces the cognitive load of the junior Sailor and redistributes it to the resulting JPA (Clark, 2014). Finally, though a training effectiveness evaluation (TEE) could be conducted to determine the extent to which Sailors learned from the JPA, this approach may be inappropriate as JPAs are not intended to produce learning but rather to be a substitute for learning (Clark, 2010). However, a TEE could still provide fundamental information regarding whether incidental learning occurred as a result of the JPA.

The EXTRACT approach is initially constrained by the use of the HoloLens 1, which only allows for limited gestures, such as 'air tap' and 'tap and hold'. Currently, the software used to implement the EXTRACT approach is being ported into the HoloLens 2, which was released mid-2020. The HoloLens 2 will allow for more robust gestures, such as 'press', 'grab', and 'direct manipulate', which will allow for a greater user experience enabling users to interact with the system in more intuitive ways. This will enhance the EXTRACT approach by affording greater usability with the system and providing a better user experience. It will also allow the approach to be more naturalistic and ultimately foster increased comfortability with the system.

ACKNOWLEDGEMENTS

The work described in this paper was funded by the Office of Naval Research (Contract #: N68335-18-C-0535) and PEO Carriers (Contract #: W911NF-17-D-0021). The authors would like to thank and acknowledge the Sailors who participated in the evaluations. Their support and availability is crucial for developing next-gen training and operational support using emerging technology that is fleet-centric and optimized for the Sailor. Additionally, the authors would like to thank Mr. Kelly Schneider, MP&T Lead for PMS 378L (PEO Carriers) for his support in the development of this effort, and Mr. Neal Jefferis of Cape Henry Associates and Mr. Kelly Holschuh of CACI for their logistical support in the execution of this evaluation.

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