Automated Assessment of Systems Engineering Competencies

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abstract

Systems engineering and technical leadership (SETL) is a multidisciplinary practice that is as much an art as a science. While a traditional model of education can teach the fundamental body of knowledge, it is not until this knowledge is put into practice in an integrated, real world environment that a systems engineer can develop the necessary insights and wisdom to become proficient. Organizations and enterprises not only need to improve the existing workforce to enable them to keep up with the demands of the work place, but also require a better approach to assess and evaluate the competencies and learnings of prospective and practicing systems engineering practitioners. Learning assessment is a critical component of accelerated learning. It is imperative to understand individual learning and the efficacy of the various learning experiences. This is critical both in determining the capabilities of the learner, but also enable the continual improvement of the capabilities of the learning experience.

This paper describes a set of Automated Learning Assessment Tools (ALATs) that measure a subject's proficiency in a set of systems engineering competencies and the efficacy simulated learning experiences through analysis of the data recorded throughout the learners' participation in a simulation experience. The vehicle that it uses is the Systems Engineering Experience Accelerator which is a new approach to developing the systems engineering and technical leadership workforce, aimed at accelerating experience assimilation through immersive, simulated learning situations where learners solve realistic problems. A prototype technology infrastructure and experience content has been developed, piloted, and evaluated. Traditionally, learning assessment has been done through examinations and experts' reviews and opinions on students' work which requires substantial effort. In addition, most approaches emphasize comparing learners' performance against those of the experts' and less about the evaluation the actual learning performance of the individuals. Though simulation has been widely adapted by systems engineering learning, it has yet to be used to assess learner competencies and learnings performance in systems engineering and technical leadership learning. The ALATs described in this paper address these issues. This paper describes the evaluation of the capabilities of these tools through their performance in a number of pilot studies. Evidence of systems engineering competencies and learning trajectories is analyzed, compared and contrasted from the perspective of the learner's performance, behaviors, self-evaluation and finally expert assessments. The limitations and strengths of the various approaches are discussed. Finally, areas of future research in pilot studies and learning assessment tool capabilities are described.

1 introduction

Due to the exponential advancement of technology, rapidly evolving needs and increasing systems complexity, it is even more challenging for educators to meet the growing educational demands for a workforce able to solve complex systems engineering problems [1-3]. Systems engineering and technical leadership are multidisciplinary practices that are as much an art as a science. While a traditional model of education can teach the fundamental body of knowledge, it is not until this knowledge is put into practice in an integrated, real world environment that a systems engineer can develop the necessary insights and wisdom to become proficient [4]. At the

same time, there is a widening gap in industry between the need and the availability of systems engineering practitioners with the necessary experience to address these challenges [1-3, 5]. Accelerated learning is one approach to address these issues. Learning assessment is a critical component of accelerated learning. It is very important to understand individual learning and the efficacy of the various learning experiences. This is crucial both in assessing the competencies of the learner, but also enable the continual improvement of the capabilities of the learning experience [6]. Automated Learning Assessment Tools (ALATs) was designed to analyze and assess learning in the accelerated learning context. The vehicle that it uses is the Systems Engineering Experience Accelerator (SEEA). SEEA is a new approach to developing the systems engineering and technical leadership workforce, aimed at accelerating experience assimilation through immersive, simulated learning situations where learners solve realistic problems. ALATs utilize the usage and performance data gathered through SEEA experience to provide automated data processing and learning analysis.

2 background

2.1 the Systems Engineering Experience Accelerator

The Systems Engineering Experience Accelerator (SEEA) project created a new approach to developing the systems engineering workforce which augments traditional, in-class education methods with educational technologies aimed at accelerating skills and experience with immersive simulated learning situations that engage learners with problems to be solved. Although educational technology is used in a variety of domains to support learning, the SEEA is one of the few such technologies that support development of the systems engineering workforce [4].

The SEEA was developed to support a single-person role-playing experience in a digital environment, as well as a specific learning exercise in which a learner plays the role of a lead systems engineer for a Department of Defense program developing a new unmanned aerial system. This exercise is based on the notion of experiential learning, and thus will be referenced as an experiential learning module. The learner engages with the experience (i.e., simulated world), makes decisions to solve problems, sees the results of those decisions, abstracts lessons learned from what was successful and what was unsuccessful, and then repeats the process in a series of cycles, simulating the evolution of the program over time [7].

The SEEA platform provides the capability to simulate the program into the future, based on these learner decisions, so that outcomes can be presented to the learner. This cycle-based decision-making process and simulation-into-the-future supports the Kolb cycle of experiential learning [8]; the experience accelerator use multiple such cycles operating through the life cycle of the program. Specifically, this approach allows illustration of the effect of upstream decisions on downstream outcomes in the system lifecycle.

Applied in an academic setting, the SEEA concept provides the possibility for a much broader scope of learning environments than a capstone project or industry internship [9]. These more traditional approaches provide a beneficial learning experience and support integrating the various components of the systems engineering body of knowledge, but are limited by time and

domain. The capstone is usually a single project and at most a year in length. If it covers the full lifecycle, then it must be a simple project and most likely represents only one domain. An internship is even more limited, given that few companies would assign a student to a significant role or provide much variation of role or domain. The SEEA envisions the ability to provide learning experiences that involve significant decision making at various levels of authority and drawn from many different domains. Neither a capstone or internship could likely present the same range of specific challenges and "aha" moments that the SEEA can provide. Whether the SEEA experience is as effective as a truly in vivo experience is part of the research underway, with results from academic and industrial pilots of the SEEA as the primary means of validating effectiveness [4].

2.2 the current learning experience

The current public SEEA experience was designed in a defense acquisition program context [10] where an Unmanned Aerial Vehicle (UAV) acquisition program is underway (Figure 1). The learner assumes the role of lead program systems engineer (LSE) just after the preliminary design review, replacing the previous lead program systems engineer. The learner is tasked immediately with identifying any existing problems with the program. The learner progresses through a set of phases corresponding to those of a real UAV acquisition program, each phase ending with an important program milestone [11]. The UAV Experience developed in the baseline year focused on developing the systems thinking, and problem solving and recovery skills of a DoD Lead Systems Engineer [6].

UAV System:
- S0 – System (UAV)
- S1 – Airframe and Propulsion (A&P)
- S2 – Command and Control (C&C)
- S3 – Ground Support (GS)

UAV KPMs:
- Schedule
- Quality
- Range
- Cost

Phases:
- EA Introduction
    - Phase 0 (P0): New Employee Orientation
- Experience Introduction
    - Phase 1 (P1): New Assignment Orientation
- Experience Body
    - Phase 2 (P2): Pre-integration system development -> CDR
    - Phase 3 (P3): Integration -> FRR
    - Phase 4 (P4): System Field Test -> PRR
    - Phase 5 (P5): Limited Production and Deployment
    - Phase 6 (P6): Experience End
- Experience Conclusion
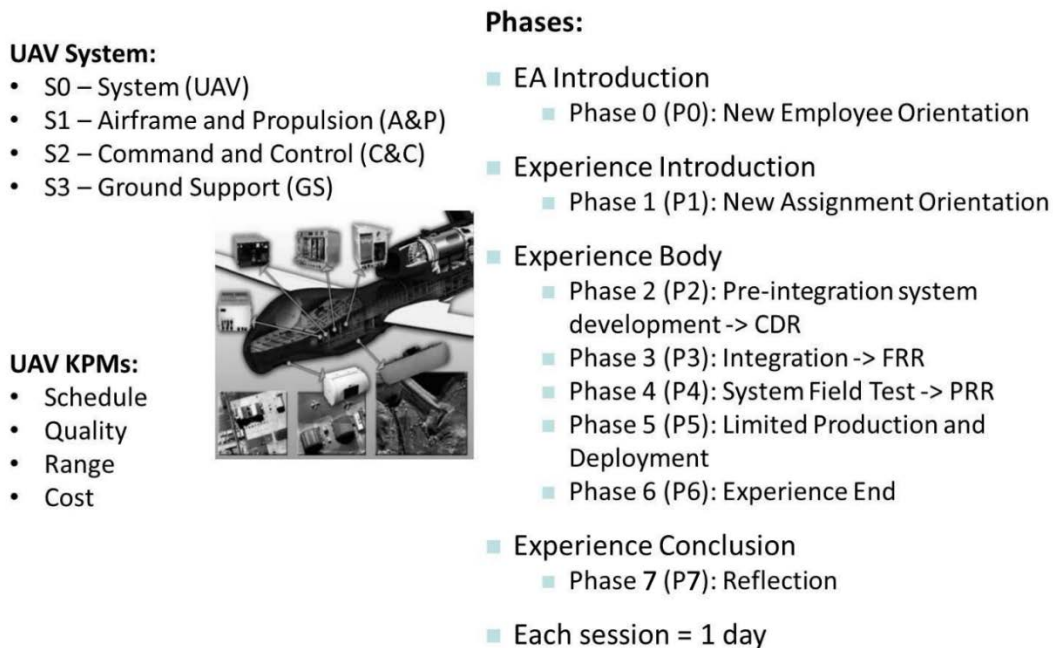   - Phase 7 (P7): Reflection
- Each session = 1 day

Figure 1 Context for the UAV Experience [6]

Phase 0 introduces the students to the SEEA and the XZ-5 program; Phase 1 explains to the students their new assignment; Phase 2 requires the students to analyze the current situation just after the completion of the preliminary design review (PDR) and make recommendations to keep the program on track leading to the critical design review (CDR); Phase 6 provides the results of

the current simulation based on the performance of the students; and Phase 7 gathers information and provides feedback to the students based on their actions taken during the experience and reflect on learning skills [9]. Phases 3, 4 and 5, simulating integration, system test and limited production and deployment were simulated to reduce the time required to complete the experience.

The UAV system under development consists of three major subsystems: The Airframe and Propulsion is primarily electro-mechanical, the Command and Control system is mainly software, and the Ground Support system is mainly human based. The key performance measures (KPMs) are schedule, quality, range and cost. Each of the learner's sessions in the Experience represent a single day in the program and are estimated to take approximately one hour to complete, although the learner is free to login and out any number of times during a session [4].

3 Automated Learning Assessment Tools (ALATs)

Traditionally, learning assessment has been done through examinations and experts' reviews and opinions based on students' course work. These approaches require substantial effort. In addition, most approaches emphasize comparing learners' performance against those of the experts' and less about the evaluation the actual learning performance of the individuals [4].

Automated Learning Assessment Tools were designed to help instructors analyze the students' systems engineering learning progress by organizing and analyzing gathered decision-making data from SEEA. SEEA captures learner approaches to decision-making (through recommendations), and by use expert choices and protocols as a baseline for "good" decision making, one can assess learner understanding.

The evaluation plan for learner performance focuses on:
- Benchmarking with an objective "score" which is also useful in motivating students
- Comparing subject matter expert (SME) SEEA actions and results to novice SE actions and results.
- Comparing SME written (or transcribed verbal) descriptions of their decision-making process during the SEEA to novice systems engineers' written (or transcribed verbal) descriptions of their decision-making process during the SEEA in experience 1 and experience 2.
- Tracking learning with changes in 1-3 above through a learner's multiple iterations through the experience.

The SEEA has been instrumented to record information as a learning laboratory. The following data has been selected and is collected from the SEEA:
- Participant Identification:
  - Learner's name & demographic information
  - Team name & other members
  - Instructor's name & roles played in experience
- Experience Session Information:
  - Experience name and version

- o Date of experience start and end
- o Login dates and duration of each session
- o Phases/cycles covered in each login session
- o Elapsed time & number of session per phase/cycle
- o Links to past experience information
  - ▪ Learner Experience Inputs & Actions:
    - o Self-assessment
    - o Initial recommendation input
    - o All subsequent recommendation inputs
    - o Workflow sequence with each action recorded with a timestamp
    - o Who is called, and which questions are asked, in which order
  - ▪ Instructor Input:
    - o Feedback provided to learners (dialog, email, etc.)
    - o Recommendations accepted/rejected
    - o Instructor's observations
  - ▪ Simulation Output:
    - o Last phase/cycle completed
    - o Results of schedule, cost, range and quality
    - o Final status charts
    - o Final score
  - ▪ Self-Reflection:
    - o Reflection feedback provided to the learner
    - o Learner's reflection input

ALATs provide the capability to visualize the experience performance data, user recommendations, and user actions. Figure 2 shows a screenshot of the Learning Analysis Tool. For example, instructor could use this tool to visualize the weight recommendation for APS department by a specific student, and analyze the actions made before each recommendation to gain insights into student's decision-making process.
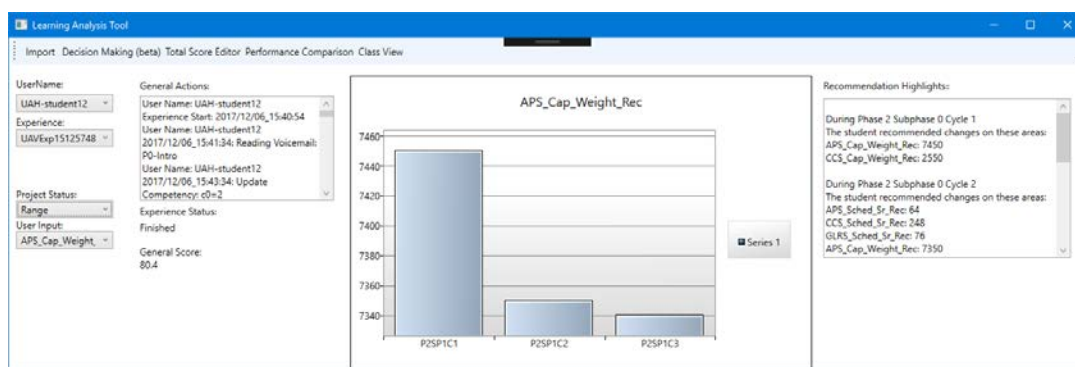

Figure 2 ALATs Learning Analysis Tool

An objective score is calculated based on learners' performance in the UAV experience. Following experts' recommendation, four critical aspects of the UAV project performance are analyzed, including Quality, Schedule, Range and Cost. Each of these aspects weights 25% towards the final score. The quality aspect focuses on total critical defects before CDR. The schedule focuses on schedule slip and average percentage of unfinished artifacts. The base value

for these aspects are one hundred (100) and points are deducted when project targets are not met. Additionally, the total score was processed with offset constants and then normalized to the scale of 0 to 100 where 0 is the case where no learner actions were made, and the 100 is the best-case scenario.

ALATs also provide instructors with ClassView feature, which can compare and contrast the performance and results of actions from different students. Figure 3 shows the screenshot of the prototype ClassView feature.
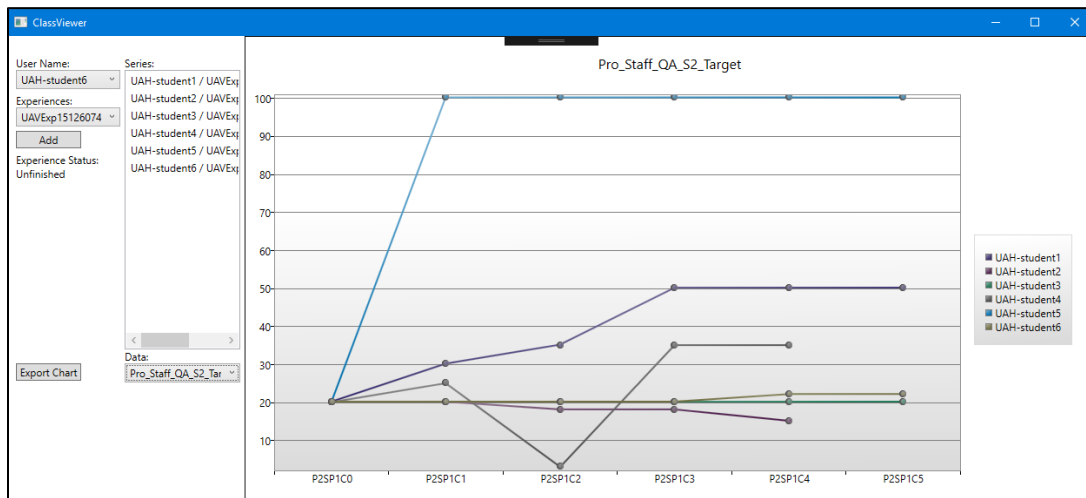
Figure 3 ClassView for ALATs

Within the UAV experience, assessment of several systems engineering competencies were implemented as part of the learning experience. These competencies include Problem Domain Knowledge, Systems Thinking, Project Management and Control Skills, and Self-learning skills. These systems engineering competencies can be assessed using a competency model through the analysis of learner recommendations and behavior. Learners' recommendations and actions reflect their decision-making process, which will also demonstrate their systems engineering competencies and skills at problem solving.

4 pilot uses of the SEEA in academic settings and results

Multiple pilot uses have been conducted through the 2016 and 2017 academic years at the University of Alabama in Huntsville (UAH), Georgia Institute of Technology (GaTech), and the Airforce Institute of Technology (AFIT). For UAH, three single run pilots and only one double run pilot were conducted due to time constraints. In a single run, the students go through the experience once from beginning to end, whereas in the double run, the students go through the entire experience twice. In GaTech and AFIT, only single run pilots were conducted.

After the pilot courses were completed, the performance data of the students were gathered and compared. The performance measures include range, critical software defects, schedule, CDR artifact completion and budget overrun. The SEEA combines these measures to determine if the CDR can be achieved successfully and determines the risk to proceed with the UAV program. During the pilot, students made different decisions resulting in a range of performances and

different program results. Among the twenty-five students participating, most of them were able to complete the whole project cycle and reach Phase 7 to receive performance feedback from the SEEA.

The data gathered during the pilot application was analyzed to provide insights on the students' decision making, their capability to discover issues in the system, their ability to prioritize resources and the outcomes of their decisions. As mentioned earlier, many different types of data are gathered by the SEEA system. Participant identification and experience session information are used to identify the specific learners and their use of the system. Learner experience inputs and actions are valuable data to track the learner's actions and behaviors during the experience, which provides insights into the learner's decision-making process. Simulation output data was used to determine the general performance for the learner and it also demonstrates the outcomes of learner decisions. Instructor input and reflections can be used to evaluate the efficacy of the learning and to improve the learning experience.

One example is in range performance. At the beginning of Phase 2, a weight increase in the Command & Control System (CCS) will cause the range to drop significantly. At this point, although the range is still within acceptable range, the trend line is very problematic.

During the 2017 spring pilot in UAH, many students expressed their concerns over the range trend and the defects trends. A common student reaction to it is to add more staff to the Airframe and Propulsion System (APS) and CCS development organizations, both to improve schedule and quality. As shown in Figure 4, Student #2 and Student #10 performed very well in the range performance area. As shown in Figure 5, both of them added staff to APS systems to the level of 80 or more staff which enabled them to successfully address the range issues. The approach also helps to reduce the drag coefficient as shown in Figure 6.
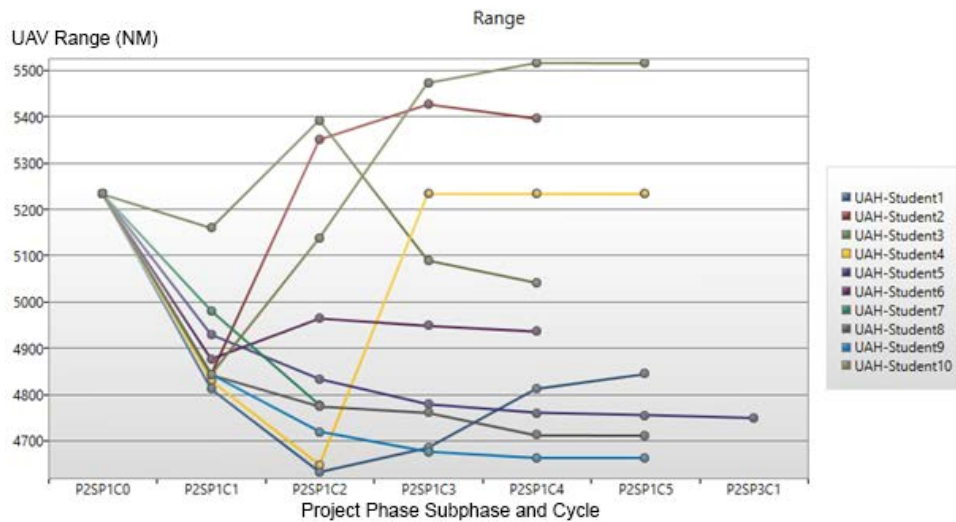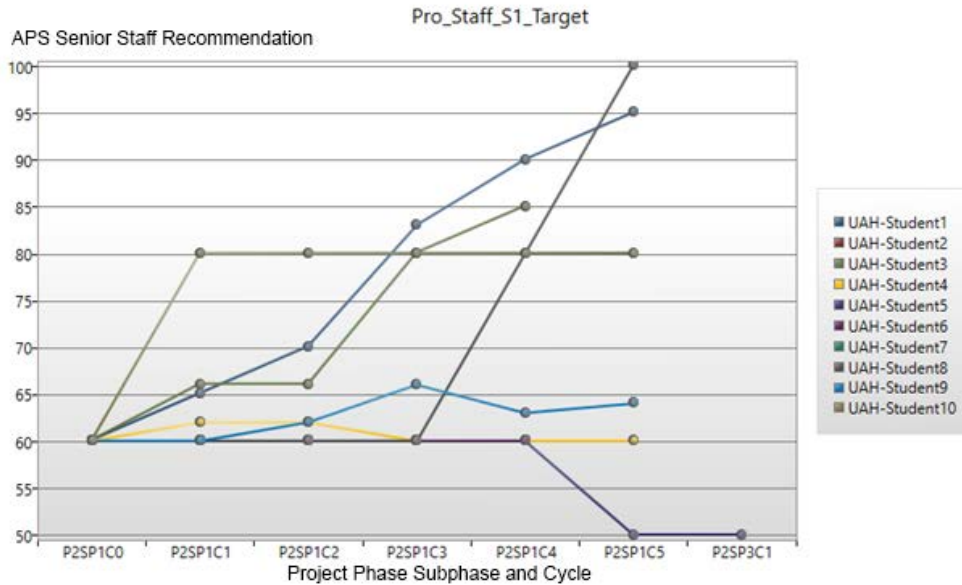

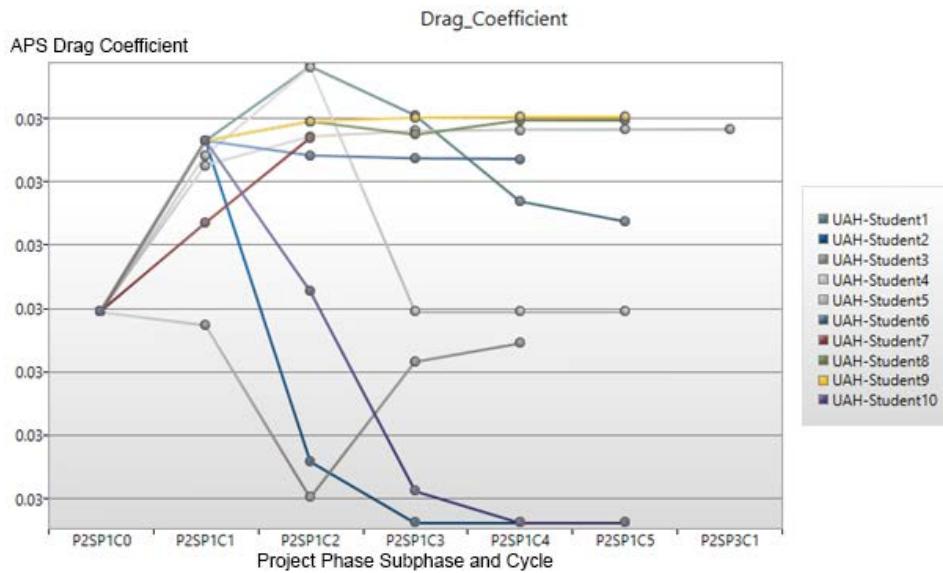Figure 4 Range Performance

Figure 5 APS System Sr. Staff

Figure 6 Drag Coefficient Performance

During the 2017 fall pilot of the SEEA in UAH, twenty-four students participated in the UAV experience. In this case, two separate pilot runs were conducted. The first experiment was performed at the beginning of the semester, and the second was performed at the end. Most students were able to complete the experience twice. The final scores for students are shown in Figure 7.
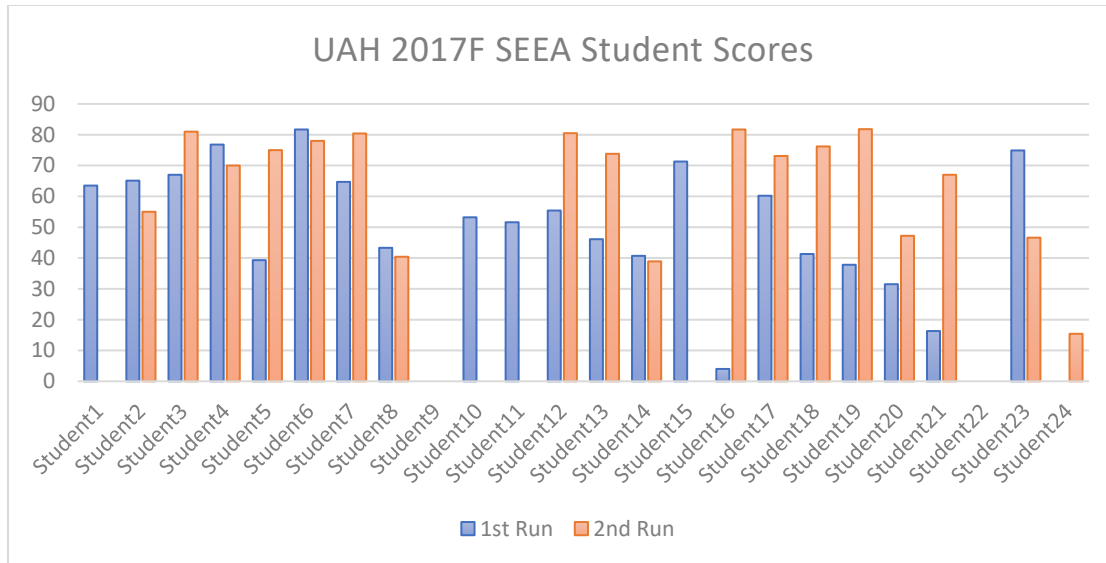
Figure 7 UAH Student Pilot Final Score for 1st and 2nd Run

Among all the students, the score of the project performance increased by an average of 17.7 points. Over 64.7 percent of students received an improved score during the second run. By analyzing the students' recommendation rationales through verbal protocol with subject matter experts, it is obvious that experiential learning has occurred among the majority of students, as they were able to demonstrate improved Systems Thinking and Project Management and Control skills. Judging from the SEEA performance data and feedback provided by the students, most of them were able to reflect, form abstract concepts and apply the concepts back to experience. This result is consistent with Kolb's concept of experience learning which consists of four key elements [12, 13]: (i) exposure to a concrete experience, (ii) reflection on that experience, (iii) generalization of the experience and formation of abstract concepts based on the generalization and (iv) application of these concepts to the concrete experience. Communication skills were also improved among students through the analysis of user-NPC dialog records, as they demonstrated increased amount critical information received from the dialogs in the second run.

There are multiple approaches available through the use of SEEA and ALATs to analyze the evidence of systems engineering competencies learning trajectories. Incorporating the findings of this research, the following assessment approaches are worth considering:
- Experts' review and examination
- Analysis of learners' in-SEEA behaviors
- Learners' project performance
- Learners' self-evaluation survey

As shown in Table 1, each approach has strengths and limitations. (i) Assessment through experts' review and examination is the most popular existing approach. While it tests learners' knowledge and understanding, it lacks the consideration of learners' hands-on skills and capabilities. This approach is also time consuming. (ii) Learner's project performance analysis provides an overall picture on the how the learner is doing with the problems in the project. The performance results demonstrate the learner's focus on the project and potential areas of improvements. (iii) Assessment through analyzing learners' in-SEEA behaviors is very useful as

it provides insights in learner's different approaches to solve the problem. It is also capable of demonstrating the learner's personal traits such as communication skills, self-learning and team playing. (iv) Learner's self-evaluation provides the instructor insights of the learner's grasp of learning progress and his/her background and previous level of proficiencies.

Table 1 Assessment Approaches

Assessment Approach	Strengths	Limitations
Expert's review and examination	Tried and true, accepted by the industry, evaluates knowledge details and understandings	Lacks consideration of hands-on capabilities and skills. Time consuming.
Learner's project performance analysis	Reflects learner's actions in simulated environment, provide insights into decision making process and hands-on capabilities	Lacks the assessment of knowledge details. Does not provide information on learner's reflection and concept generation steps during learning.
Learner's behavior analysis	Provide insights in learner's attempts to solve problems. Demonstrate traits like communication and self-learning skills.	Lacks the causal relationship if used alone. Does not take into consideration the learner's background and capabilities level before learning.
Learner's self-evaluation analysis	Provide vital information on learner's self-reflect learning process. Provide assessment from learner's perspective. Useful for instructors to improve the learning experience.	Lacks the objective view of the learner's capabilities and skills. Results varies vastly depending on learner's personal style.

Though each approach can be used separately, a hybrid approach can provide a more balanced and complete view. One method of combining these approaches is to use experts' review of the information and insights provided by the SEEA and ALATs together with traditional means of assessment. This approach provides experts with experience-based information so that real-world learners' capabilities and skills can be assessed and potentially projected.

Feedback from the instructors was very positive as they indicated that "the value of the SEEA and ALATs is that it integrates into a dynamic simulation several of the key concepts covered in the systems engineering class, including:
- Technical performance measurement and tracking,
- Margin management,
- Earned value management,
- Risk analysis,
- The systems life cycle, and
- Technical reviews.

As such, it greatly augments the lectures and homework assignments for these topics, which tend to be focused on only one of these interrelated topics."

5 conclusion and future works

This research developed a set of Automated Learning Assessment Tools (ALATs) that measure a subject's proficiency in a set of systems engineering competencies and the efficacy simulated learning experiences through analysis of the data recorded throughout the learners' participation in a simulation experience. A SEEA prototype technology infrastructure and experience content has been developed, piloted and evaluated. During the multiple pilot uses of the SEEA, ALATs were used to analyze students' systems engineering competencies and learning trajectories. Through the analyses of the gathered performance and behavioral data during multiple pilot uses, the SEEA provides the capability to benefit the learner's systems engineering learning process. Learners' performance score improved an average of 17.67 points between multiple run of the experience, and among students who completed both runs, over 64.7 percent of students demonstrated an improved performance during the second run. Furthermore, the data gathered by SEEA also provides insights into learner's decision making and information analysis process making future training more productive.

The future area of work for this research include gathering data through pilot application with a number of systems engineering experts; use data gathered from expert pilot use of SEEA and ALATs to calibrate the experience and scoring mechanism; compare students' behavior data and decision-making process with experts'; further explore the efficacy of a hybrid assessment approach which uses experts' review of the information and insights provided by the SEEA and ALATs together with traditional means of assessment; and potentially add new capabilities to increase the degree of automation in assessment.

6 acknowledgements

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