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Teaching Digital Twins

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Digital twins (DT) differ from digital models and even from digital shadows in that the virtual twin (in silico twin) can influence the physical twin and vice versa. The influence of the in-silico twin is determined by significant processing of data provided by various sensors on the physical twin and other sources, both historical and environmental. Artificial intelligence and machine learning can be used alongside data science algorithms to perform projections and forecasting, and to perform optimizations for the physical twin. The results of the calculations cause the in-silico twin to adjust actuators in the physical twin, and to monitor those changes. In a digital shadow, the physical twin sends data to the in-silico twin which then can use that data to run projections and optimizations; humans must adjust the physical twin. Digital models are simulated representations of the physical system, but with no sensor-driven data feeds from the physical system to the model. In contrast with control systems which focus on immediate feedback and control loops, DT can run predictions, in near-real-time, and can synthesize data from many sources into their algorithms to optimize system performance. DTs can be used for scenario simulation and are being used in prototyping and operational testing.
The scope of application of DT is far-reaching and has touched several domains already. Large complex systems are being fitted with appropriate sensors and actuators to enable this technology. Manufacturing is one of the early adopters of this technology, but DT are being successfully implemented in a variety of domains including production systems[1, 2], agricultural systems[3], utility systems [4], healthcare systems [5], and military systems[6]. While there are discussions on the use of digital twins in systems engineering [7], there is no course or textbook and few instructional materials are available outside of articles about the promise of the technology or a specific implementation.

DT technology is rapidly growing into its own field, straddling data science, computer science, artificial intelligence, electronics, visualization, and systems engineering. As such, it must be embedded in the education of professionals in these fields, especially systems engineering. Systems engineers envision, design, and oversee the implementation, operation, maintenance, and retirement of systems and will be called on to specify and incorporate DT technology in many ways, yet there is no training focused on DT. This gap motivated the development of the course *Fundamentals of Digital Twins*. The goal of this course is to inform systems engineering students about some of the considerations they will need to make in the design and implementation of DT for systems.

This work describes the experience in teaching a pilot offering of the graduate course *Fundamental of Digital Twins* in the Systems Engineering program in the department of Engineering at the University of South Alabama. The six students that comprise the pilot class have backgrounds in Computer Science, Artificial Intelligence, Electrical Engineering, Civil Engineering, Process and Control Engineering, and Forensics.

Table 1 - Course Structure and Content

Week	Topic	Sub-topic(s)	Objectives
1	Motivation/Application	Vocabulary Readings Short Course	Student shall be able to distinguish and define the differences between intelligent digital twin, digital twin, digital shadow, and digital model.
			Student shall be able to describe where digital twins fit into one or more domains of interest.
2			Students will become familiar with the pedagogical approach to the class.
3	Digital Spaces	C# Programming 3D Graphics	Students will install and use Unity.
4			Students will be able to create a scene, add objects to it, and animate the movement of those objects.
5			Students will learn how C# is used within Unity and the resources available to them for writing code.
6	Physical Spaces	Python Programming Electronics	Students will become familiar with reading wiring diagrams and creating the circuits with kit materials.
7			Students will learn simple programming in Python to control various lights and actuators.
8			Students will apply systems engineering principles (requirements, test, etc.) to the construction of a model of a smart farm.
9			Students will use provided code to become familiar with the sensors and actuators available in the smart farm.
10	Digital Twin Development	Design	Students will design a virtual smart farm to be used as a simple digital twin.
11		In-silico twin	Students will implement their virtual smart farm in Unity.
12	Communications	Serial WiFi	Students will modify provided code to control the physical model with the in-silico model.
13			Time permitting, students will experiment with the WiFi communication available on the ESP32 Dev Board.
14 15			Students will contrive an experiment that demonstrates the implementation of a true digital twin of the physical smart farm.
16	Presentation		Students will present their digital twin implementation.

Developing and teaching a pilot course is not without its challenges. Some of the challenges addressed are working with diverse skill levels in the students, managing the tools and equipment necessary for the development of both the realized and virtual twin and teaching the course as an on-line offering. Additionally, various technical issues encountered during the course is addressed. Observations from the instructor are shared, and insights from not only dealing with these challenges but breakthrough moments are included. Student feedback was actively solicited during the pilot offering, and an analysis of these comments is provided, alongside incremental and future improvements planned for the course.

The course is defined as a 3-hour credit graduate course offered as an elective. One credit corresponds to 9 hours of work per week including lecture time. The course planning consists of topic identification, material selection, pedagogic form, course realization, and course evaluation. This course is currently in its pilot offering so no past evaluation can be discussed. The primary learning goals are represented by the lesson objectives as seen in Table 1 - Course Structure and Content

Motivation/Application

Vocabulary: Appropriate vocabulary is defined based on industry standards [8]. Students were introduced to the differences between digital models, digital shadows, and digital twins. Other terminology including intelligent digital twin and edge computing is also discussed. Students without prior mechanical or chemical process engineering experience are introduced to the concepts of sensors and actuators.

Table 2 - Assigned Readings

Year	Title	Authors	Publisher
2020	Digital Twin: Values, Challenges and Enablers From a Modeling Perspective [10]	Rasheed, Adil San, Omer Kvamsdal, Trond	IEEE Access
2021	Digital Twin System Interoperability Framework [8]	Budiardjo, Anto Migliori, Doug	OMG Digital Twin Consortium (White Paper)
2024	Industry Use Cases		Unity (White Paper)
2021	Differentiating Digital Twin from Digital Shadow [11]	Sepasgozar, Samad M. E.	Buildings
2023	Unlocking the Potential of Digital Twins [2]	Manickam, Sabrina Yarlagadda, Laasya Shynu, P. G. Chowdhary, Chiranji Lal	IEEE Access
2019	Leveraging Digital Twin Technology in Model-Based Systems Engineering [7]	Madni, Azad M. Madni, Carla C. Lucero, Scott D.	Systems

Readings: Papers (shown in Table 2 - Assigned Readings) are assigned for reading throughout the course. Additionally, the book Mirror Worlds [9] is assigned reading. Students were encouraged to research the application of digital twin technology to their system or domain of interest. Systems engineering students study a wide range of systems and so specific application papers and examples are not always understood or appreciated due to lack of domain knowledge. As systems engineering embraces DT technology, more readings specific to various systems engineering processes and areas will be available and incorporated into future course readings.
Short Course: The short course, *Digital Twins with Unity* (https://learn.unity.com/tutorial/introduction-to-digital-twins-with-unity), is required viewing. The actual implementation of an example of a twin visualization at the end of the short course is demonstrated and discussed during an on-line course session.

Digital Spaces

Given the disparate backgrounds of systems engineering students, no prior experience with either programming, electronics, or 3D graphics could be assumed.
Programming: For the C# programming instruction, the Unity course *Create with Code* (https://learn.unity.com/course/create-with-code), was followed. Visual Studio was used as the code editor. For the Arduino programming (Python), *Hero Introduction Training* (https://learn.inventr.io/courses/introduction-class/) and *30 Days Lost in Space* (https://learn.inventr.io/courses/adventurekit30dayslostinspace-2023/) were taken by the students. Arduino IDE was used as the code editor.
3D Graphics: In addition to the programming, *Create with Code* introduced a wide range of capabilities of the Unity game engine. Modifications were made to the lessons to emphasize the techniques that would be utilized later in the course (object movement and interaction, lighting, sound, etc.) in the development of the DT.

Physical Spaces

Electronics: The two courses, *Hero Introduction Training* and *30 Days Lost in Space* were intended as an introduction to electronics as they assume no prior knowledge. The physical twin system was an IoT kit shown in Figure 1 - Keyestudio Smart Farm. This kit included all parts needed for the assembly and running of the smart farm (except batteries). Throughout the construction of the model, testing was intended to be conducted to ensure sensors and actuators were functioning properly. Course milestones included the successful completion of the physical and digital models.

Digital Twin Development

Students were provided with a variety of ways in which to plan their DT. The requirements were that they needed to be able to influence the physical system through some sort of digital trigger, and to provide a digital effect to physical system sensor data. The motion sensor, light, and buzzer were suggested to achieve this. Students discussed and documented their plans and were encouraged to use assets from the Unity store to build a somewhat realistic DT. Since a precise digital representation, or even one of high fidelity, was not required, students displayed some creativity in their virtual farms.

Communications

Serial: The Hero board (used in the two introductory classes) and the ESP32 Dev Module (used in the smart farm) were connected via USB to a computer. Programs were written that sent and received data from the physical twin and the computer, either the Arduino IDE or in the Unity environment.

WiFi: The smart farm kit can communicate via WiFi. The students are provided with sample code and may elect to use this capability in the twin implementation, time permitting. This was not part of the instruction.

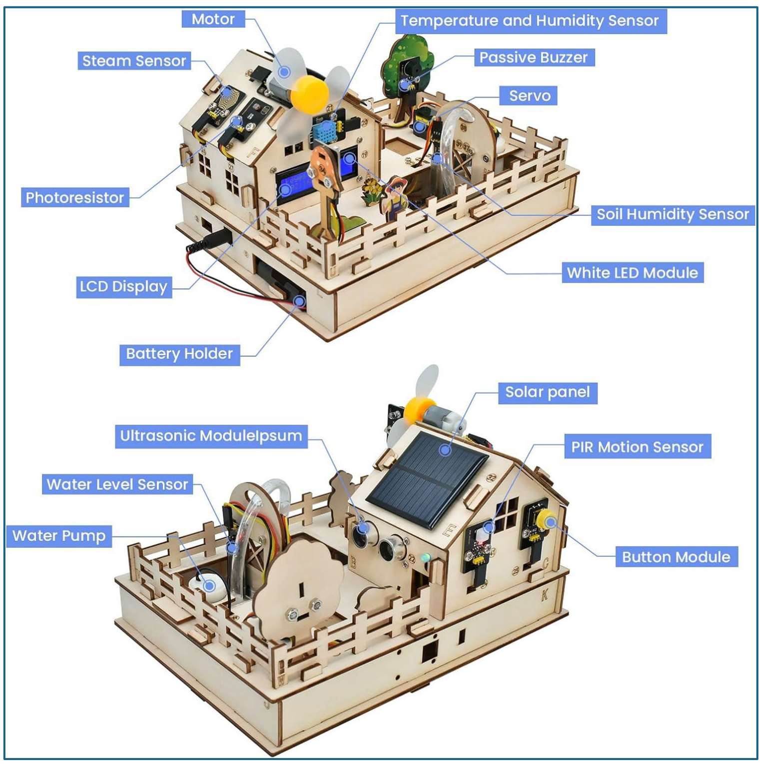

Figure 1 - Keyestudio Smart Farm

There is a preponderance of scholarly articles about research opportunities and spaces, and a growing number of papers describing implementations of DT. A selection of these papers was provided to the students, and the ones in Table 2 were assigned reading and discussed during class. Students were encouraged to research and find applications of digital twin technologies in their domain of interest and present their findings to the class.

As we offer more courses remotely, there is a concern about a lack of hands-on experience. The instructor and half of the students in the pilot course are not on campus, requiring this course to be taught remotely – students and instructors would not have physical access to each other. The challenge was then to develop a meaningful hands-on course that could be guided remotely. Canvas was used as the Learning Management System.

Table 3 - Assignments and Grades

Task	Description	Weight
Unity Essentials	Student submits a screenshot of their solution to a 3D puzzle	1.5%
Create with Code	Student submits a video of the game they created (player movement)	4.5%
Create with Code Unit 2	Student submits a video of the game they created (collision)	4.5%
Create with Code Unit 3	Student submits a video of the game they created (particles and sound)	4.5%
Create with Code Unit 4	Student submits a video of the game they created (lighting and effects)	4.5%
Create with Code Unity 5	Student submits a video of the game they created (user interface)	4.5%
Smart Farm Model	Student submits a photograph of the completed model.	22.5%
Discussion – Why is this a better way?	Check point discussion about Day 9 in 30 Days Lost in Space lesson.	1.5%
Design Ideas	Student submits a design document for the digital twin.	7.5%
Virtual Twin	Student submits a video of their digital twin in action. Student submits an updated design document.	22.5%
Code for the Twin	Student uploads the Sketch file that runs the physical twin and the Unity project file.	22.5%

The course incorporated a live session via Zoom each week where students and the instructor could ask questions, discuss topics, and obtain assistance with wherever they were in the progression of the class. Deadlines for assignments were very flexible, and students were not in lockstep as would happen in a classroom setting. The expectation was that the students would spend approximately 9 hours per week on the course; the live sessions usually ran for 90 minutes. Homework assignments were planned so that they could be realized in 5-10 hours of work and were designed to move the students through the external training in a timely manner. The final project, the implementation of the digital twin of the physical farm, could start in week 8 after sufficient information about the physical farm was obtained. Many students did not start with the development of the digital farm until week 10. The course was 16 weeks in duration.

At the conclusion of the semester, a student perception of instruction instrument is administered by the University. Students are encouraged to fill out the form and provide feedback on the course and instruction. The same instrument is used for all courses across the University where students can rank their course on a scale of 1 to 5, 5 being the best. Individual student responses are not provided to the instructor, only the measures of mean, standard deviation, and median. These numbers are used to compare relative success of courses. All six students provided a response.

Two thirds of the way through the course, a Google form was created to obtain feedback from the students. This form asked several open-ended questions of the students, including "What could/should be dropped from the course, and why?" and "What should be added to the course, and why?". These two questions were also asked during a class session and discussed with all present.

Table 4 - Student Perceptions Scoring

Scope	Mean	STD	Median
Course	4.5	1.00	5.0
Department	4.12	1.26	5.0
College	4.09	1.22	5.0
University	4.30	1.05	5.0

From the student perception of instruction instrument, the course was seen as a success itself and when compared to scores of other courses in various scopes. The course score, 4.5, indicates that students did not just give top scores, but provided feedback. The comments on the student perception instrument, provided anonymously, mirrored the mid-course feedback. From the synchronous discussion sessions and the Google forms, the class indicated that the *30 Days Lost in Space* course was unnecessary. The instructions provided with the smart farm kit were detailed enough to guide the model construction even by a novice. Two students with no electronics experience (Civil Engineering and Forensics) skipped the *30 Days Lost in Space* course entirely, indicating it was not necessary to include this course. As these two completed their smart farm kit, they expressed that even the *Hero Introduction Training* course was not necessary for them to build and use the smart farm kit. Class discussion revealed that all the students generally agreed with this feeling that more information about programming would have been helpful. The discussion progressed as the students thought about all the things they would have had time to do had that course not been included, including more time exploring the DT and experimenting.

Overall, the course appears to have been successful. This is based on the feedback from the students and their ability to apply what they learned over the semester in 3D graphics, C# and

Figure 2 - Virtual Farms for DT (top left to right Monday, McLeod, Tarale; middle Seger; bottom left to right Pandit, Robinson).

Arduino programming, and electronics to produce a functional physical system and it’s DT. As seen in Figure 2, the virtual twins varied considerably. In the lower right corner, the physical model is also shown.

Now knowledgeable about the possibilities of this technology, three of these students have indicated that they will be using DT technology in their research. The other three students are at the start of their research and have not selected a research project but acknowledge that this is an avenue they now have available to them and will consider. Students did indicate that they wanted to go back to learn more about Unity capabilities to improve their DT after viewing everyone's final presentation.

The additional coursework from inventr.io – *HERO Introduction* and *30 Days Lost in Space* – while informative and straightforward, was not required for the successful completion of the electronics work. The manufacturer of the solar farm kit provided updated materials for assembly and tests that enabled students who did not do the inventr.io courses to be successful in the construction of the physical system model. In the next iteration, the inventr.io courses will be omitted. Based on feedback, more time will be spent on communication between the twins and sample code for both serial and WiFi communications will be included. Additionally, time will be spent in the process of data capture and analysis for predictive modeling with the DT.

Given the concern that a remote education is missing a critical hands-on component, this course clearly demonstrated that a hands-on laboratory experience can successfully be a part of a remote classroom. If this course were given in a classroom setting, it would be more difficult allowing students to work at their own pace without providing distraction to fellow students. While there might be more student-student interaction, we had considerable interaction in the Zoom sessions and students reached out to each other outside of class. None of the students expressed a regret that the course had not been face-to-face.

Additional offerings of the course over the next few years will provide additional data and feedback to further refine the course and instruction. The research efforts of the six students who have completed this class will be monitored to help gage the impact of this course in their research.

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