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Integrating Digital Twin Technologies into the Group Design Project for the Advanced Air Mobility Systems MSc Course

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Abstract: This study aims to develop the content and material for the Group Design Project (GDP) with Digital Twin (DT) technologies, aligned with Future Flight Challenge (FFC) project deliveries involving Cranfield, the emerging Research and Development (R&D) capacities, and the increasing demands for talent and workforce from the industry. The GDP delivery and learning approach, structured as a five-phase process - project and technical management, Concept of Operations (ConOps) and requirements definition, system development, case study and evaluation, and final results - is stated in the paper. This proposed approach has been evaluated with the AAMS 23/24 academic year MSc GDP.

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Keywords: Advanced Air Mobility Systems, Group Design Project, Digital Twin, MSc Course, V Model.

1. INTRODUCTION

The emergence of transformative automated and autonomous technology in both crewed and uncrewed air traffic management (ATM) systems, including new, sustainable, and intelligent aerial platforms, to transport people and goods, represents the next cornerstone in the aerospace industry's ongoing evolution. In this context, the UK government and industry proposed the Future Flight Challenge (FFC) to establish a roadmap for the development of a new aviation system in the UK by 2030 (UK Research and Innovation, 2021). As an important academic participant in FFC programmes, Cranfield University has been involved with 9 projects in FFC Phase 2 programmes and 4 projects in FFC Phase 3 programmes. In line with the ongoing evolution of future flight, Cranfield has gained extensive experience, expertise, and Research and Development (R&D) infrastructures around the future flight area. The future flight markets and industry trends create a significant demand for talented graduates contributing to unlocking the full potential of Advanced Air Mobility (AAM) applications (Zhao et al., 2023b).

In this context, the Advanced Air Mobility Systems (AAMS) MSc course was designed and delivered during the 2022/2023 academic year (Zhao et al., 2024). As one of the three core components of the AAMS MSc, the Group Design Project (GDP) facilitates the design, construction, and operation of autonomous solutions for the emerging AAMS market, modernized and integrated crewed/uncrewed Traffic Management, thus integrating and applying the knowledge students acquire in the taught modules. Additionally, the GDP aims to provide students with experience in collaborative engineering projects within an industry-structured team environment, developing transferable skills that include teamwork across diverse backgrounds and areas of expertise, project management, and technical presentation skills.

The GDP is developed based on industrial, research, and teaching inputs. Industrially, the Industrial Advisory Board (IAB) for the AAMS MSc course, along with collaborators from related projects, contribute by providing practical experience and insights. They offer use cases that reflect the evolving field of AAM, thus bridging academic learning with current industry trends. Research inputs derive from the outputs of various projects and activities. Notably, completed and ongoing projects like the UK Research and Innovation (UKRI) FFC Phase 3 Project Air Mobility Ecosystem Consortium (AMEC), Project BLUEPRINT, Project HADO, and the SESAR SAFIR-Ready project provide vital knowledge and expertise for GDP development. Teaching inputs encompass contributions from the teaching team and the use of resources, equipment, and facilities. Notable among these are the Air Traffic Management/Uncrewed Traffic Management Research and Development Digital Twin Environment (AURD), a cloud-based system facilitating the simulation, interfacing, and testing of AAM systems, subsystems, and components. The research conducted by the researchers is integrated into this environment as library toolsets. Additional teaching resources include the Cranfield Global Research Airport, the National Drone Innovation Gateway, and the Digital Aviation Research and Technology Centre (DARTeC), along with the HILDA high-performance computing ecosystem and the Research Digital Tower (r-TWR) (Zhao et al., 2023a). These facilities and equipment are pivotal to the advanced infrastructure necessary for the project.

The AURD is an AWS cloud-based Digital Twin (DT) system that enables the safe, scalable, and sustainable development, verification, and validation of AAM systems, subsystems, and components (Zhao et al., 2023a). It consists of the physical world, the virtual world, the connectivity, and the data module, based on the environment, vehicle, and traffic levels (Conrad et al., 2023; Turco et al., 2024; Wen et al., 2024). This DT environment has been integrated into the ATM Lab's research

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and teaching activities and will form the foundation for the proposed GDP approach. It will provide critical capabilities for developing and delivering the GDP.

The paper aims to integrate the aforementioned industrial, research, and teaching inputs into the DT-based GDP to ensure that the project remains at the forefront of academic and practical advancements.

2. METHODOLOGY

The GDP approach is based on the classic Systems Engineering 'V' model (Graessler and Hentze, 2020) and NASA's system design process (Shea, 2017) to facilitate system design. As shown in Fig. 1, the proposed approach encompasses the required activities to capture requirements, design solutions, and define all Test and Evaluation (T&E) activities. The approach consists of five stepwise processes: Manage – Project and Technical; Define – Concept of Operations (ConOps) and Requirements; Develop – System Development; Evidence – Case Study and Evaluation; and Result – Documentation, Reporting, and Assessment. In detail,

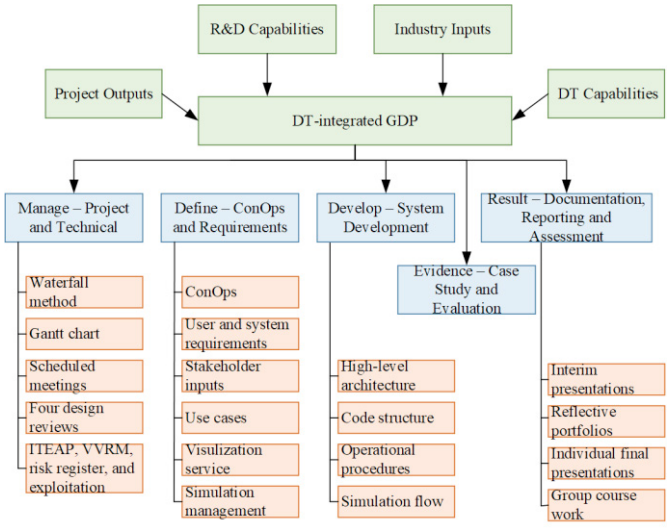


Figure 1. The proposed GDP approach.

2.1 Manage – Project and Technical

The Waterfall method is adopted throughout this project, being the most suited approach for a time-constrained work plan with clearly defined system needs and periodic documentation requirements. In alignment with this strategy, a Gantt chart is created, highlighting the project timeline used to develop, integrate, test, and document a DT prototype. Additionally, the roles and responsibilities of each team member are meticulously planned.

The GDP meetings encompass AAMS MSc Cohort weekly meetings, bi-weekly supervision meetings that include external stakeholders, and monthly progress reporting meetings. Besides these regular gatherings, a kick-off meeting and a final presentation meeting are also scheduled.

In terms of engineering management, regular design reviews are planned. These include Concept Design Review, Preliminary Design Review, Critical Design Review, and Final Design Review. The timing of these review meetings is strategically scheduled. Other important aspects of engineering management, such as Integrated Test, Evaluation, and Acceptance Plan (ITEAP), Verification and Validation Requirements Matrix (VVRM), risk register, and exploitation activities, are also scheduled and conducted.

Important deliverables include the ConOps report and final GDP reports.

2.2 Define – ConOps and Requirements

The initial stage of the GDP involves producing the ConOps and requirements. The ConOps describes the characteristics of the proposed system, including the capture and management of User Requirements (URs), which define a need met by the proposed system through its characterization (system description) and implementation (operational employment).

Stakeholder Requirements and Inputs: The stakeholders of the GDP include Cranfield ATM Lab and industrial partners such as SkyPorts and NATS. These partners provide their requirements and support the definition of the ConOps and use cases. The Cranfield team supplies the GDP with a Single Statement of User Need (SSUN), requirements, and existing capabilities to conduct research and technical activities. An example of general stakeholder requirements is illustrated in Fig. 2. Inputs from the Cranfield course team include the AURD.

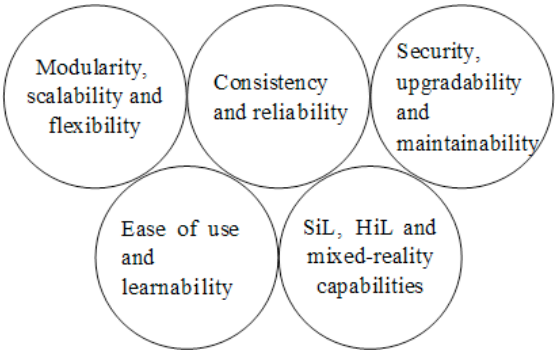


Figure 2. An example of general stakeholder requirements.

Use Case Definition and ConOps Development: In this task, the AAMS MSc cohort conducts a system literature review, defines and down-selects the use cases with the support of the stakeholders, and then develops the ConOps.

User and System Requirements Definition: The ConOps facilitates the derivation of URs, which encapsulate all the functions of the required system. Once all URs have been captured and agreed upon, a small number (ideally fewer than ten) of Key User Requirements (KURs) are identified and agreed upon. The KURs are fundamental to the project and, if not met, the system will fail to meet the User's Requirements. The combination of ConOps, system technical description, and coherent URs should completely describe the system, which can then be assigned System Requirements (SRs). The SRs ensure the system will actually perform as required.

2.3 Develop – System Development

In alignment with the four design reviews, the DT architecture is developed to meet the identified product requirements. An overview of the underlying code structure is provided, highlighting how modularity, scalability, and flexibility were prioritized throughout the design process. Additionally, the operational procedures required to add, modify, or remove elements within the architecture are systematically documented. These procedures also cover those needed to execute specific simulations.

The DT encompasses virtual environments, user interfaces, and custom modeling for vehicles and sensors. It also outlines the methodologies used to realize the underlying algorithms for each identified use case. Finally, the procedure used to deploy the entire prototype is detailed, highlighting all system dependencies and requirements.

2.4 Evidence – Case Study and Evaluation

The developed DT will be systematically evaluated through case studies. These studies are designed to assess the effectiveness and efficiency of the DT system in a controlled environment, providing critical insights into its operational viability and scalability.

2.5 Result – Documentation, Reporting and Assessment

Based on Cranfield University's academic thesis template, a modified GDP final report is produced by the course team. This report incorporates both the group elements and technical work. The list of the content from the template is displayed in Fig. 3.

Chapter 1 - Introduction 1
Chapter 2 - Literature Review 17
Chapter 3 - System Requirements and Project Management 46
Chapter 4 – Methodology and System Architecture 58
Chapter 5 - System Implementation and Case Studies 68
Chapter 6 - Results, Testing and Evaluation 86
Chapter 7 - Conclusion 110

Figure 3. The list of the content of the GDP report template.

In terms of Assessment and Feedback, the methods include interim presentations, reflective portfolios, individual presentations of the group project, and group coursework.

3. CASE STUDY AND RESULTS

3.1 Case Study with 23/24 AAMS MSc GDP

Following the proposed approach in Chapter 2, a GDP entitled "A Digital Twin System for Vertiport Design and eVTOL Operations" was delivered by the 23/24 AMMS MSc cohort. A simplified Gantt chart created by the GDP cohort is shown in Fig. 4. The project formally spanned three months, from January 8, 2024, to April 12, 2024. A preparation phase starting on October 17, 2023, was allocated to acquire the necessary knowledge and skills. Four regular design reviews were placed during the project as important milestones.

TASK	START	END
WP1 Initiation		
T1.1 User Requirements	17-Oct	8-Jan
T1.2 Define Scope	17-Oct	31-Oct
T1.3 Literature Survey	8-Jan	28-Feb
T1.4 Use-Case Finalization	31-Oct	8-Jan
WP2 Planning and Design		
T2.1 Create High Level Project Architecture	8-Jan	22-Jan
T2.2 Define Project Management Method	8-Jan	22-Jan
T2.3 Define Database Management	8-Jan	22-Jan
T2.4 Define ConOps	8-Jan	10-Feb
WP3 Environment Modelling - Vertiport (VP) Development		
T3.1 Identify Vertiport Specifications	22-Jan	10-Feb
T3.2 Preliminary Design of vertiport	29-Jan	10-Feb
T3.3 Create CAD Model of vertiport	10-Feb	20-Feb
T3.4 Build Environment Around the VP	20-Feb	24-Feb
WP4 Integration with AirSim and Unreal Engine		
T4.1 AirSim Integration	24-Jan	27-Jan
T4.2 Bringing eVTOL in Unreal Environment	22-Feb	2-Mar
T4.3 Python Client for AirSim	22-Feb	2-Mar
WP5 Use-Case Implementation		
T5.1 Engine Failure	22-Feb	12-Mar
T5.2 Adverse Weather	22-Feb	12-Mar
T5.3 Weather APIs	12-Mar	15-Mar
T5.4 Intelligent Algorithims and Hough Circle	12-Mar	16-Mar
T5.5 Trigger Box	12-Mar	15-Mar
WP6 Evaluation		
T6.1 Validation of Weather Use Case	15-Mar	3-Apr
T6.2 Validation of Engine Failure	15-Mar	3-Apr
T6.3 Computing the Delays to Simulate the Operations	17-Mar	12-Apr
T6.4 Coding Part for Computing Delays Caused by EF	17-Mar	12-Apr
T6.5 Mixed Reality	17-Mar	12-Apr
T6.6 Report Writing	18-Mar	12-Apr

Figure 4. A simplified Gantt chart from the 23/24 AMMS MSc GDP cohort.

By the formal kick-off of the project, the stakeholder inputs were in place, and the requirements for the GDP are illustrated in Fig. 5. The Cranfield AURD was also provided to the cohort as the basis for the GDP. By the end of the Concept Design Review, the ConOps and requirements were finalized, with the ConOps document serving as an important deliverable for this phase. The key requirements and selected use cases are clearly defined in the documents, with examples of Key System Requirements shown in Table 1. The three main use cases addressed are Adverse Weather, Engine Failure, and Intelligent Solutions.

By the end of the Preliminary Design Review, following the design methodology in the ConOps, the DT system for vertiport design and eVTOL operations was further refined. Fig. 6 illustrates the overall DT architecture, and Fig. 7 shows the digital vertiport and eVTOL operations.

By the end of the Critical Design Review, the use cases simulating various vertiport operations during adverse weather and engine failure in the eVTOL were conducted. Fig. 8 illustrates the case of engine failure.

By the end of the Final Design Review, the Verification and Validation (V&V) was completed, demonstrated in Fig. 9 with the use of a mission planner to validate the developed DT.

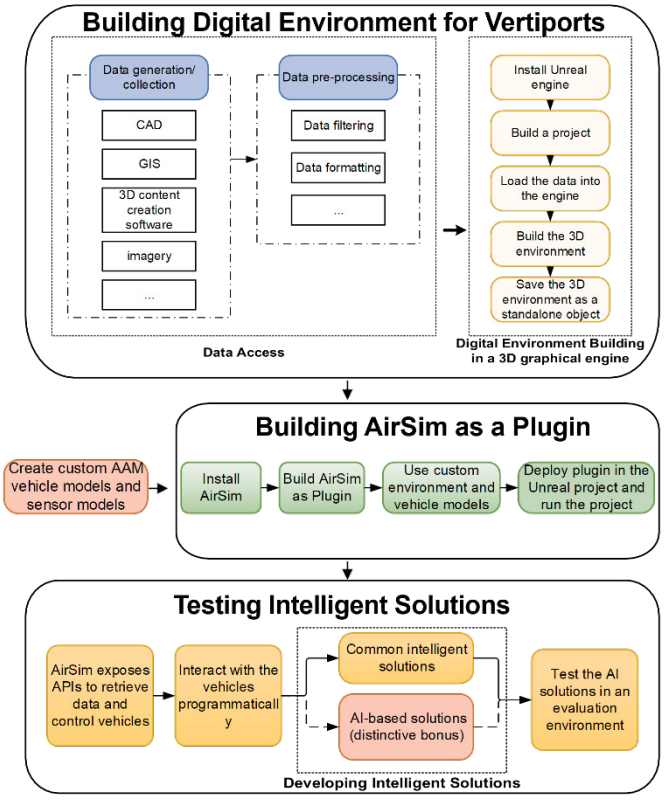


Figure 5. The stakeholder requirements for the GDP.

As a result, a DT for vertiport operations was developed in the GDP. An in-depth analysis of how the existing vertiport operates identified key areas for improvement through DT and AI technology, specifically focusing on the adverse weather and engine failure use cases. The project detailed the process of building the DT model, including constructing the 3D environment, executing virtual simulations, testing the model's responsiveness, and using the API to import implementation weather data. The GDP outputs were compiled in the final report, and individual presentations of the group project allowed students to showcase their work. Reflective portfolios were submitted by the students to provide summative feedback on the team members and the GDP.

3.2 Feedback and Recommendations

The GDP received feedback from the GDP cohort through Reflective Portfolios, as well as from academic and industrial stakeholders during the module delivery and review phases. Here is a summary of the feedback and lessons learned:

Project Structure and Management:

- Project Focus: The initial scope of the project was overly ambitious, leading to significant shifts in focus, such as the removal of the fire safety and battery monitoring use cases. A more narrowed focus from the beginning could prevent effort from being spent on ultimately irrelevant tasks.
- Initial Clarity: Changes in the project's aims and user requirements after including industrial stakeholders led to inefficiencies. Clear, consistent initial definitions of project goals and requirements are crucial.
- Team Size and Interaction: A smaller team size, ideally 4-5 members, would enhance focus and reduce conflicts. Additionally, replacing biweekly presentations with regular progress meetings and Q&A sessions could focus more on problem-solving and less on formal presentations.
- Use of Industry Examples: Showcasing similar works at the beginning of the course could prevent misunderstandings and set a clear frame of reference.
- Timeline and Feedback: More specific feedback from the industrial stakeholders on the relevance and priority of tasks during the project could prevent wasted effort on less critical activities.
- Assessment: Group elements are the most important part of the assessment. Individual presentations should be replaced by a group presentation, as individual contributions have been evaluated in the Reflective Portfolios.

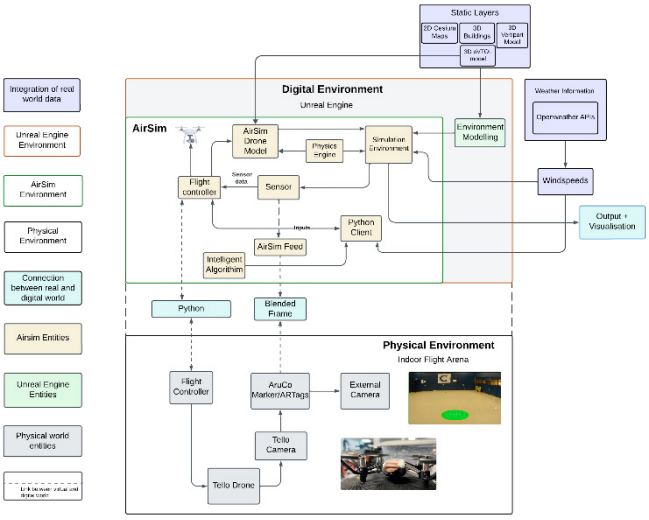


Figure 6. Overview of the proposed DT architecture.

DT Accessibility:

- DT System Familiarity: Limited understanding of the DT hindered the process of the GDP. Training sessions on the DT platform and tools like Unreal and AirSim are suggested to better prepare students for their practical application in the GDP.
- Resource Solutions: The software requires high GPU and CPU performance. This suggests a need for better upfront planning regarding software requirements and capabilities. Including essential software like Unreal Engine on HILDA or lab computers could make it accessible to all students, facilitating smoother progress in software-related projects.
- Exploration and Use Cases: The exploration of DT and the definition of achievable use cases were areas

where too much time was lost without adequate guidance. Early and clear definition of use cases, especially achievable ones with the available software and hardware, is recommended.

Table 1. Examples of Key System Requirements

Category	Statement of Requirement
Environment Modeling	The system must support the creation of indoor and outdoor digital environments for simulation purposes.
Intelligent Algorithms	The DT must support the implementation of intelligent algorithms.
HiL and Mixed Reality	The system must support hardware-in-the-loop (HiL) simulations and mixed-reality demonstrations for testing and validation.
Scalability	The DT must be able to scale and replicate multiple scenarios and environments.
Usability	The DT interface must be user-friendly.
Performance	The system must maintain real-time response capabilities.
Accuracy	Environmental modeling and UAS behaviors within the DT must closely mimic real-world conditions.
Extensibility	The architecture of the DT should allow for easy updates and integration of new features.
Documentation	Comprehensive documentation must be provided for system architecture, code structure, and operational procedures.

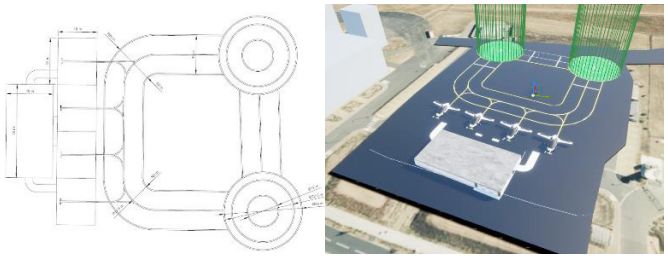


Figure 7. The 2D and 3D vertiport design.

Stakeholder Involvement:

- Industry Interaction: Interactions with industry partners, such as Skyports and NATS, were inconsistent, occasionally missing meetings, which disrupted continuity. Regular, perhaps mandatory, engagements or even offline meetings with all stakeholders could improve collaboration and commitment.
- Academic Guidance: More specific guidance and support from academics are necessary. Involved researchers can support technical training in addition to supervision.



Figure 8. A snapshot of the engine failure use case.

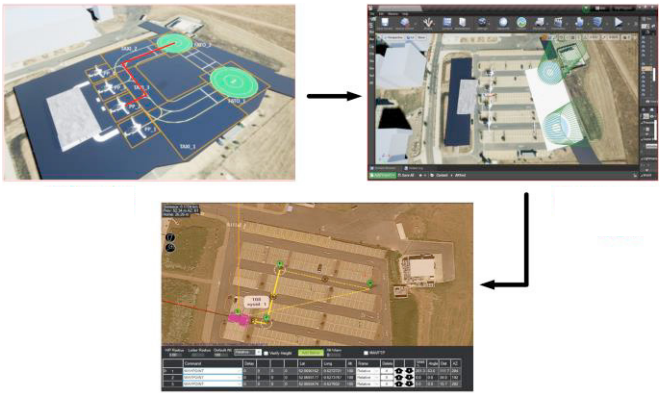


Figure 9. A snapshot of the mission planner evaluation.

Student Project-level Skills:

- Decision-Making and Meeting Efficiency: It is beneficial to make decisions promptly during focused discussions instead of postponing them, which can streamline project progress and reduce confusion.
- Communication and Responsibility: Enhancing communication skills is essential for expressing ideas clearly and understanding the perspectives of others. This could help ensure more cohesive team efforts.
- Engagement and Awareness: Being informed about all aspects of the team's work helps in making well-rounded decisions and adapting to changes swiftly.
- Effective Time Management: Prioritising tasks, setting realistic deadlines, and using time management tools can help enhance productivity and ensure on-time delivery of projects.
- Clear Roles and Accountability: Organizing into smaller teams from the beginning could provide clearer responsibilities and enhance accountability.
- Diverse Interests: There is value in showing interest in areas of the project that one hasn't directly worked on. This broader interest can contribute to a more

well-rounded understanding and involvement in the project.

4. CONCLUSIONS

This paper proposes a GDP delivery and learning approach that integrates DT technology into MSc level group projects. The proposed approach has been evaluated with the AAMS 23/24 academic year MSc GDP.

The conclusions drawn from this study are as follows:

- The DT technology proves to be an effective tool in MSc GDP due to its ability to leverage both simulation-based and practical research. Its capability to integrate various simulation tools as co-simulators and interface with diverse AAM systems, subsystems, and components makes it an ideal platform for AAM studies. Moreover, the incorporation of additional DT technologies such as cloud computing, 3D simulation, data mining, and the Internet of Things (IoT) significantly enhances its utility for studies focused on autonomy and intelligence.
- Research project outputs, R&D capacities, and industrial inputs were successfully integrated into the GDP approach, enriching the learning experience and relevance of the project.
- According to the evaluation results from the AAMS 23/24 MSc GDP, the proposed approach is effective. Some enhancements shall be made for the next academic year.

As for future work, the enhancements stated in section 3.2 to address these issues raised by students and stakeholders will be further developed.

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