Continuous Testing and Deployment for Urban Air Mobility

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***Abstract*—The Urban Air Mobility (UAM) market is rapidly growing, but UAM manufacturers face a number of significant issues. Among these are development times and cost, complex regulatory requirements, and the need to secure aircraft against cyber threats.**

Traditional development practices and tools used in the avionics industry are insufficient to meet the needs of UAM developers. The multi-year development lifecycles common in the aviation industry are ill-suited to the fast-paced and competitive UAM market. For UAM manufacturers to succeed in the marketplace, it is necessary to leverage DevOps development practices and hardware virtualization to reduce overall lifecycle costs and, in turn, ensure the ability to meet the customer's vehicle safety and cost requirements.

Keywords—Urban Air Mobility (UAM), DevOps, virtualization

I. INTRODUCTION

The Urban Air Mobility (UAM) industry is designed to address the mobility needs of rapidly growing urban areas. A number of different organizations have entered the space in an attempt to capture a percentage of the estimated $500 billion market [1].

While the commercial market for "air taxis" is a large portion of the intended target market of UAM vehicles, it is not the only one. UAM vehicles have been proposed for use in last-stage parcel delivery, autonomous cargo transport vehicles, and for military applications.

As a result, the UAM industry has received support from a number of industry verticals. In the private sector, Uber has emerged as a leader with its Uber Elevate initiative [2].

In the U.S. public sector, the National Aeronautics and Space Administration (NASA) has announced a Grand Challenge to help spur UAM development [3]. Also, the U.S. Department of Defense (DoD) has announced the Agility Prime Initiative that offers use of its test facilities and other resources to help development of UAM vehicles that may be purchased later for military use [4].

II. CHALLENGES FACING UAM MANUFACTURERS

Despite the strong support from the avionics industry and potential customers, UAM manufacturers face a number of major issues that must be overcome before vehicles can be approved for production and operation. Major potential challenges are delivery timelines, safety regulations and standards, and the need to secure potential vehicles against cyber threats.

A. Development Costs and Timelines

The UAM market has already demonstrated itself to be extremely competitive. Many companies have already demonstrated proof of concept vehicles, and others are being encouraged to enter the market through initiatives such as the NASA UAM Grand Challenge.

A major inhibitor to organizations wishing to enter the UAM market is the time and cost associated with developing vehicles that meet consumer needs. The government imposes strict standards on the avionics industry such as the Federal Aviation Administration (FAA) and the European Union Aviation Safety Agency (EASA) regulations [5]. Additionally, consumers demand a safe product that is also affordable.

Meeting the required safety standards of the industry requires extensive testing of components and software in a range of failure conditions. However, accomplishing this with physical components can be prohibitively expensive for many organizations. A test rig can cost up to millions of dollars for avionics systems, and most development teams require multiple rigs to complete necessary testing on-schedule. Due to the growing complexity of avionics systems and increased reliance on software, software development is anticipated to account for 88% of total system costs by 2024 [6].

Additionally, the costs associated with design and testing of physical components and software do not end with production. Aircraft systems, like all software, requires periodic updates, and, avionics manufacturers are slow to release updates. For example, the DoD's Defense Innovation Board (DIB) has target update release timelines of one to three months for functionality upgrades and less than one week for security patches [7]. However, on average within the DoD, these processes take one to five years and one to 18 months respectively.

In order to meet the regulatory requirements of the avionics industry, many manufacturers use traditional design methods, such as Waterfall, and perform extensive testing on physical components. In the UAM industry, where time to market is essential for profitability, this approach may not be applicable.

B. Regulatory Requirements and Safety Standards

The avionics industry is held to a high regulatory standard with regard to safety. On average, commercial aircraft experience less than 0.6 fatal accidents per million flights [8]. Before an aircraft is permitted to enter large-scale production and be sold to airlines or the military, it must undergo an extensive certification process.

While safety regulations for the UAM industry have not yet been defined, it is probable that they will be held to a higher standard than commercial aircraft due to a number of reasons:

- *Autonomous Operation.* UAM vehicles will either be remotely piloted or self-piloted, so piloting systems must be demonstrated to be capable of properly handling errors.
- *Vertical Takeoffs and Landings.* UAM vehicles will be forced to takeoff and land vertically in tight environments, which introduce new safety issues.
- *Operating Environment.* UAM vehicles will be operated in densely-populated, urban environments, unlike commercial aircraft that largely travel over sparsely-populated, rural areas.

Achieving compliance with commercial aircraft regulations and standards, such as DO-178C can be expensive for a manufacturer. In fact, projects requiring DO-178C compliance are at least 15-65% costlier than projects with no compliance requirements [6]. The introduction of DO-326A compliance regulations, as well as any UAM-specific standards, will only increase the cost of vehicle manufacture and regulatory compliance.

C. Cybersecurity Considerations

Commercial aircraft has a growing potential cyber-attack surface as upgrades to navigation technology and other in-flight systems connect them to the Internet. These aircraft commonly receive updates "over the air" that could be intercepted by an attacker.

UAM vehicles, due to their unique operating conditions are even more potentially vulnerable to attack. Many UAM vehicles will have remote operators as either a primary or fallback piloting option, which will require network connectivity. Additionally, passengers of UAM vehicles will have physical access to unmanned aircraft, which could be leveraged for malicious purposes.

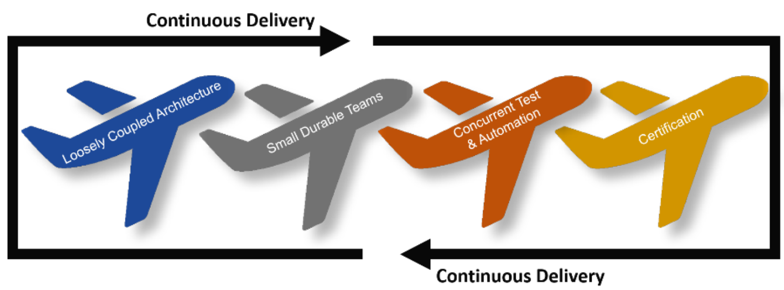
Ensuring the security of aircraft is complicated by the fact that most vehicles are a "system of systems". Different components are manufactured by certain vendors, so a UAM vehicle is likely to be a conglomeration of a variety of different systems. This level of complexity makes manual security analysis challenging and increases the probability that one system is a "weak link" that can be exploited for access to the rest of the system.

The long lifetimes of vehicles and infrequent update cycles exacerbate these problems. If a vulnerability has been discovered within a particular component, it could be a very long time until a patch is available and widely applied. During this window, an attacker could potentially take advantage of the vulnerability to exploit and gain access to the system.

Despite all of these challenges, the need to secure UAM vehicles against cyber threats will be necessary for them to be accepted by regulatory authorities. In 2019, the FAA made compliance with DO-326A mandatory for aircraft manufacturers seeking airworthiness certification [9]. This regulation requires manufacturers to address potential cyber threats to their vehicles' systems.

III. APPLYING DEVOPS TO UAM

Figure 1. Application of DevOps



The need for correctness in avionics means that many companies have adopted waterfall or other similar legacy development practices. Through exhaustive planning, these methodologies are intended to ensure that no errors creep into a system during the design phase. However, these approaches are poorly-suited to UAM development, where rapid testing is necessary to meet compliance requirements and gain market share.

DevOps is a software engineering culture and practice designed to bridge the gaps between development and operations. By leveraging modular design, automation, and continuous integration and deployment (CI/CD) practices, DevOps enables teams to expedite software delivery, identify errors earlier in the process, and adapt rapidly to meet evolving customer needs (see Figure 1).

Currently, 48% of organizations have transitioned from legacy development practices to following the tenets of DevOps for all development, and 27% applying it selectively [10].

For DevOps to be effective, an organization must fully support it and structure teams, workflows, reporting requirements, and evaluation criteria appropriately. Attempting to follow DevOps practices while performing team and project planning and evaluations undercuts the DevOps process and robs the organization of many of its benefits. However, fully embracing these practices can provide significant advantages to UAM manufacturers.

A. Principles of DevOps

DevOps development practices combine the principles of the Agile development methodology with the use of available technology. The use of automation throughout the development process improves the speed and accuracy of development.

The Agile and DevOps mentality is based upon modularizing software. Rather than designing and creating a single, monolithic system, DevOps breaks the system into pieces and independently creates each one with well-defined interfaces between components. This simplifies the design and developments processes and reduces the probability of errors. In fact, elite development teams following DevOps practices have a change failure rate 7x lower than low performing development teams [11].

Another core principle of DevOps is the practice of continuous development and testing. Before a code commit is accepted and added to the repository, it undergoes a range of functionality and security tests. This enables any errors to be detected as early as possible, minimizing the technical debt incurred by the need to rewrite existing code to eliminate design and implementation errors.

B. DevOps Benefits for UAM

DevOps practices are a valuable tool for developers in general. However, for the avionics industry, and UAM manufacturers in particular, they provide a number of crucial advantages. Among these are the ability to rapidly correct errors and to increase the delivery speed of code that meets regulatory requirements.

1) Rapid error detection and correction

The safety of passengers and bystanders is critical to the acceptance of UAM vehicles by regulatory authorities and potential customers. An error in the design or implementation of the system could result in either a loss of certification, if discovered during testing, or a potentially fatal accident if it arose during production use.

The best way to reduce the impact and cost of software errors is to detect them as early in the development process as possible. The longer that an error remains undetected, the more code that must be revised to remediate it and the tighter the window before release. As a result, correcting an error in development can be 100 times cheaper than fixing one in production code [12].

Adoption of DevOps practices can help UAM manufacturers to reduce the costs associated with design or programming errors. Continuous integration and testing increases the probability that an issue will be detected early in the development process, minimizing the cost of correction. Modularized code with well-defined interfaces between components simplifies code review and limits the amount of code that would be affected by an error.

2) Increase speed of delivery

Regulatory compliance is a major concern for UAM manufacturers. While several proof of concept vehicles exist today, the regulatory standards that define the requirements for them to be permitted to operate are not yet defined.

Once regulatory standards have been defined, and assuming that these regulations follow formal documentation requirements as is required for today, the adoption of DevOps processes and tools can help developers to ensure that a proposed design is compliant with applicable regulations throughout the development process. For example, formal documentation including requirements, test results, structural coverage, traceability etc. can be time consuming and complex. The focus in DevOps on continuous integration and automation enables developers to generate these regulatory artifacts at any time. This helps to decrease the time and cost associated with the certification process since a new baseline of certification artifacts can be generated immediately after the software has been modified. In addition to unit tests and security tests, continuous integration and testing systems can include tests for regulatory compliance.

IV. HARDWARE EMULATION FOR UAM

Conceptually, DevOps practices are well-suited to the avionics industry in general and UAM vehicles in particular. However, they are only half of the solution to the problems facing potential UAM manufacturers.

In order to be effective, DevOps requires the ability to perform continuous integration and testing. However, the systems that avionics code run on are costly, making it prohibitively expensive to run the large number of parallel tests required by DevOps on physical hardware. This is why hardware virtualization is essential to the rapid and affordable development of UAM vehicles.

A. Avionics Hardware Virtualization

Avionics uses embedded systems, which makes automated testing for DevOps challenging. These systems are specialized and expensive, limiting the number of test rigs available to development teams.

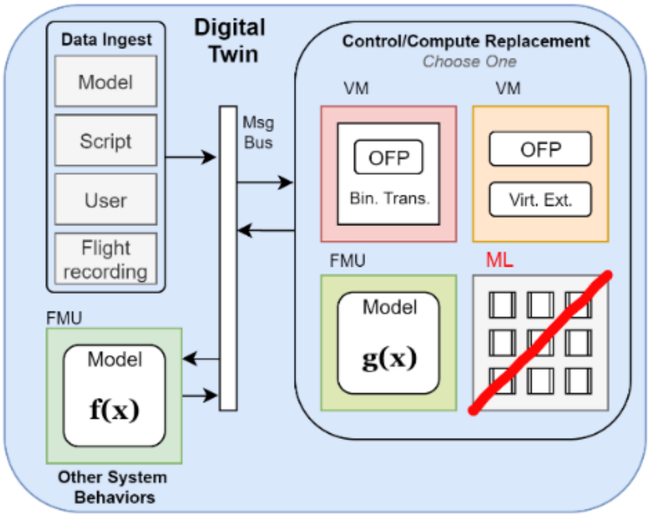
Full hardware virtualization helps to solve this problem. By creating a complete and accurate replica of the hardware target environment, it is possible to perform realistic testing of software in the emulated environment.

The development of virtualization technology can be as expensive as purchasing the physical hardware. The use of Commercial off-the-shelf (COTS) solutions with pre-built models for common avionics components, such as the JETS virtual platform, can be used to significantly reduce costs.

With full hardware virtualization, a “guest” virtual machine (VM) designed for the same instruction set as the target system is all that is needed for testing. The full hardware virtualization system performs emulation of the physical hardware within operating parameters of real systems, enabling realistic testing of software within the VM.

As shown in Figure 2, virtualization also enables developers to take advantage of a variety of control and computation replacement options.

Figure 2. Sample Architecture of Virtualized Digital Twin



This transition from physical hardware to a virtualized environment enables testing to be performed at a scale that is impossible or prohibitively expensive with physical hardware. Additionally, functional testing on emulated hardware may be accepted for formal certification credit [13]. However, hardware virtualization does have its disadvantages such as slower speed of execution, inability to vet out system performance and speed, and potential additional licensing costs.

B. *Advantages of Virtualization for UAM*

Hardware virtualization technology makes it possible for avionics manufacturers to effectively adopt and scale DevOps practices. This provides significant advantages in regard to development speed, cost of development, ability to achieve regulatory compliance, and the complexity of identifying and mitigating potential cyber threats to systems.

1) Expedited development

The use of virtualization reduces or eliminates the dependence of the development team on physical hardware. This can help to dramatically speed up the development process.

One major impact of hardware emulation for the development of UAM vehicles is the ability to begin software design and testing much earlier in the process. UAM vehicles will require custom components, meaning that software tests on physical hardware must be delayed until the hardware design is finalized and physical components have been manufactured. With full hardware emulation, development and testing can commence as soon as the hardware is designed and appropriately emulated in the virtualized environment.

Virtualization also dramatically increases the scalability of developers' test environments. With fully virtualized hardware and access to cloud-based infrastructure, developers have access to virtually unlimited computational power to perform simulated tests. This enables tests to be performed on-demand and in parallel. The use of virtualization also enables tests for software developed to run on legacy hardware to be executed more rapidly without compromising test integrity.

This additional scalability enables UAM developers to perform the continuous integration and testing required by DevOps. The use of emulated hardware and VMs means that testing can be automated as part of the DevOps pipeline, and additional test environments can be spun up as needed. As a result, testing can be performed at-need and in a fully-automated fashion, enabling the detection of vulnerabilities and other errors early in the development process.

2) Decreased development costs

In addition to time savings, virtualization also dramatically decreases overhead costs associated with development. Automated, virtualized testing reduces dependence on physical test rigs and developer time.

A physical test rig for avionics software can be prohibitively expensive. The use of full hardware virtualization, built with pre-certified COTS solutions, enables the replacement of procured hardware for most or all of developers' testing requirements. Each developer can have their own copy of the emulated hardware at their desktop, eliminating release delays due to limited access to procured hardware.

Often, the limited availability of physical hardware forces organizations to run round-the-clock tests with the available rigs to meet deadlines. This practice can be expensive - due to the need to compensate workers with unusual or extended schedules - and damaging to morale. With virtualization, testing capacity can be scaled as needed without requiring developers to work night shifts for vital testing. In addition, scaling benefits in providing the ability to reduce the overall time to complete verification and validation.

3) Regulatory Compliance

Achieving certification under applicable regulations is necessary for aircraft to be approved for use. Testing against applicable regulations, such as those enforced by the FAA, throughout the development process reduces this burden.

Full hardware virtualization provides a huge advantage for this since emulation environments can be used for formal testing. Certain types of testing would require qualification of the VM as a verification tool to prove the interfaces duplicate the physical hardware, including hardware interfaces for [13]:

- Interrupt handling
- BIT to failure detection
- HW/SW interfaces
- Control of memory management hardware or other hardware devices under SW control
- Stack overflow
- SW partitioning
- Responses to hardware failures
- Behavior of control loops
- Single event upset detection
- Software timing that is the result of timer-driven interrupts or hardware-driven timer activities
- Bus/resource contention issues

- Responses to hardware transients

In general, the FAA is positive toward the use of virtualization for testing of avionics software and currently pushes these technologies in its technology capital plan [14]. Beyond realistic emulation, it looks favorably on the fact that virtualized systems can use fault injection to simulate failure cases that would be difficult or destructive to test with physical hardware.

With hardware virtualization, developers can run simulated tests against compliance requirements throughout the development process. This helps to ensure that systems meet compliance requirements without costly physical builds, and emulated tests can be used to gain credit toward compliance certification with regulatory authorities such as the FAA and EASA.

4) Improved system security

With the enforcement of DO-326A, ensuring the security of avionics systems against cyber threats is essential for certification of UAM vehicles. The use of hardware virtualization as part of continuous integration and testing provides several advantages to UAM developers:

- Supports security testing with advanced diagnostics and debugging of potential vulnerabilities
- Enables single-step debugging, traces, logging, and root-cause analysis
- Makes possible the integration of heterogeneous virtual machines running different architectures, operating systems, and applications for "system-of-systems" simulations and testing
- Enables rapid verification of patches and updates to component system parts while ensuring no unintended ripple effects to the system as a whole

These capabilities simplify the process of testing software for vulnerabilities that could impact software security or eligibility for certification. Additionally, virtualization enables testing to be performed with every code commit, minimizing the impact and technical debt associated with detected vulnerabilities.

V. CASE STUDIES

As a safety-critical industry, avionics manufacturers often prefer to remain with "tried and true" tools and techniques. This has resulted in a reluctance to adopt "untested" development processes and tools such as DevOps and hardware virtualization.

However, some organizations have adopted these processes and tools in their development environments. Through the use of DevOps and/or hardware virtualization, avionics manufacturers have sped up development processes, reduced software defects, expedited regulatory compliance reporting, and improved the efficiency of vehicle safety checks.

A. Expedited Development

A global avionics systems supplier was tasked with building a Flight Management System (FMS) for a major aircraft supplier. The avionics supplier had 20 physical test rigs available to them, but 70 were required to meet critical delivery schedule deadlines.

Through use of hardware virtualization, this supplier was able to meet delivery deadlines [15]. Supplementing the twenty physical test rigs with 50 virtual ones enabled all 70 developers to perform testing in parallel. As a result, the complete set of 19,000 required tests was completed in hours instead of weeks.

B. Reduced Error Rates

The Space and Intelligence Systems section of Harris Corporation has adopted DevOps principles [16]. This includes the use of CI/CD for development of software for communication systems, space and intelligence systems, and electronic systems.

Beyond the improvements in software delivery times, a 50% reduction, Harris has also experienced a marked decrease in software defects of 58%. In a safety critical sector, such as avionics, elimination of defects helps manufacturers to ensure the safety of their passengers and security and usability of their vehicles.

C. Regulatory Compliance

In the avionics sector, regulatory compliance requires a great deal of testing. All of this testing requires extensive documentation, which can be extremely complex and time-consuming to generate.

Airbus, a leading aircraft manufacturer, has embraced automation for managing their reporting requirements [17], in accordance with DevOps principles. Previously, the company manually generated Microsoft Office documents with test results, which were often difficult to tie to regulatory and test requirements.

Now, tools integrated into their testing process automatically generate Word documents containing test procedures, reports, test results, and compliance records. This use of automation has enabled Airbus to save time and money and made them more competitive in the marketplace.

D. Passenger Safety

With UAM vehicles, the safety of the passengers and bystanders is of vital importance. Performing regular testing of critical systems is important to ensuring that a vehicle is flightworthy. However, these tests can be time consuming, which decreases the time that a vehicle can be operating and profitable.

An aviation manufacturer has previously faced this same issue with their aircraft [18]. Previously, engine health checks for these planes took 24 hours. Ideally, the manufacturer wanted this time decreased by 50% to 12 hours.

To achieve these goals, Kubernetes-clustered microservices were deployed in a private cloud. During testing, the engine's software sends its test results to a digital twin in the cloud. This supports rapid predictive analytics that provide an analysis of the engine's safety prior to takeoff.

By embracing DevOps and automation, the aircraft manufacturer dramatically decreased maintenance delays due to engine health checks. Instead of the target test time of twelve hours, engine health checks only require three hours. This is an eight-fold reduction in test time with no negative impact on passenger safety.

VI. CONCLUSION

Traditional development processes for avionics, such as the use of the Waterfall development model and physical testing rigs, are a poor choice for the development of UAM systems and software. UAM is a rapidly-moving field with strict regulatory requirements, so modern development processes and technologies are required.

As UAM manufacturers consider toolchains for continuous testing and deployment, virtualization should be considered as one of the top choices for increasing the quality of testing. Virtualization, in combination with the use of DevOps processes and tools, also helps to reduce the overall cost of validation and verification.

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