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Investigating Possible Effects of UAVs on Aircraft Carrier Deck Operations

ABSTRACT

In the near future, unmanned aerial vehicle (UAV) and unmanned ground vehicle (UGV) usage will expand into the Naval aircraft carrier operating environment. The new and different capabilities of these vehicles will likely introduce numerous potential changes in the nature of deck operations. The presence of UAVs and wireless data communications will enable centralized planning and control of launch and recovery schedules, leading to fundamental changes in the nature of launch and recovery events. Moreover, the effect of UAVs and UGVs on total manpower and man-hours of labor required to execute launch and recovery tasks is unknown. However, these changes may further alter the number of crew and amount of labor required in order to accomplish launch and recovery tasks. To this end, a simulation of aircraft carrier deck operations has been created that incorporates models of manned aircraft, crew, deck support vehicles (e.g. tow tractors, fire trucks) and deck resources (catapults, elevators and arresting gear) as well the ability to alter various factors governing the environment, UAV behavior and physical dimensions of aircraft and the ship. This effort examines the potential force reductions that UAVs may enable for aircraft carrier deck operations. Specifically, the effects of aircraft roster composition (all manned, all unmanned, or mixed), unmanned vehicle behavior (slower or faster than manned aircraft) and UAV autonomy (number of crew required) on the number of crew required and the workload of these crewmembers are investigated. These effects are weighed against a measure of mission performance for launch operations.

INTRODUCTION

A 2005 Naval Studies Board report [1] called for the United States Navy to accelerate the implementation of Unmanned Vehicles (UxVs) in air-, land- and sea-based operations. Included in this report was the acknowledgement that Unmanned Aerial Vehicles (UAVs) "with a high degree of autonomy can potentially reduce training, support rapid changes in tactics, … enable reductions in force personnel and help reduce the logistics footprint" of the modern Navy. The reduction of required personnel generated by the implementation of UxVs accomplishes a second goal of increasing the safety of carrier flight deck operations. The replacement of the pilot with an unmanned system will directly reduce pilot risk by removing them from combat. A second safety goal may be achieved on the deck itself, where highly autonomous systems requiring less human interaction allow these crew to be relocated from a typically highly dangerous environment. The crew filling these roles need not be completely removed from the ship, and could be instead transferred to other areas around the ship to increase the effectiveness of operations there, or even to other ships within the fleet.

To achieve the goal of UAV integration in carrier operations, the Navy is currently funding two major programs for the development of highly-autonomous fixed-wing UAVs – the UCAS-D program, begun in 2007 [2] and the new UCLASS program, begun in 2011 [3]. As the aircraft developed by these programs are integrated into flight deck operations, the differences in their behavior (as compared to manned aircraft) may lead to numerous operational changes on the aircraft carrier deck. These changes, as noted by the Naval Studies Board, are primarily dependent on the level of autonomy with which the vehicles operate. This includes not only how vehicles are controlled and the manner in which they interact with crew, but also in respect to the proficiency with which the vehicles accomplish tasks on the deck.

Two primary ways in which UAV autonomy may influence manning projections are by reducing the number of crew required to interact with UAVs and by increasing the ability of the UAV to execute tasks (potentially increasing the operational tempo). Reductions in crew interactions may be induced by increasing the level of autonomy of the control of the UAV. Viewed in line with Sheridan and Verplank's levels of automation [4], UAV control ranges from remote piloting (General Atomics' MQ-1 Predator [5]) to semi-autonomous systems capable of executing task-based control (like the X-47B [6]) to fully autonomous vehicles capable of planning and executing their own tasks without human interaction. In this latter case, fewer crew are needed to interact with a given vehicle at any time. Additionally, if UAVs are capable of performing tasks with minimal human assistance (e.g., if UAVs have preplanned routes and do not have to wait for the instructions of crew members) a greater level of efficiency may be possible on the carrier deck. This would require increases in vehicle sense-and-avoid capabilities during taxi (improving on the autonomous cars of Google [7] and the DARPA Urban Grand Challenge [8, 9]) and the ability for UAVs to autonomously detect and orient themselves to catapults and arresting gear, among other objects. These capabilities are achievable using onboard sensors, such as laser range-finding ([10]), to detect and guide vehicles to a target. Although these technologies have the potential to reduce staffing on the carrier deck, reducing crew levels beyond a certain threshold may limit the operational effectiveness of the aircraft carrier in launching and recovering aircraft and provide a net detriment to operations.

A real world test of the effects of a UAV's implementation on carrier operations cannot be performed until the aircraft has successfully completed carrier qualifications and been cleared for flight deck operations. However, the use of a simulation of carrier deck operations may allow some insight into potential effects of UAV implementation prior to this milestone. Recent work at the Massachusetts Institute of Technology has resulted in the creation of a simulation environment for aircraft carrier flight deck operations [11], modeling the behavior of crew, manned and unmanned aircraft, support vehicles on the deck, the deck itself (catapults, landing strip, fueling, etc.) and the myriad failures that may arise in any of these items during operations. Through this simulation environment, the effects of UAV behavior on the flight deck can be explored without the large capital investment needed to enact real-world testing.

This research leverages this simulation environment to examine how the level of autonomy and proficiency with which UAVs operate may affect the efficiency of deck operations and the resulting workload of the crew. These evaluations show that current staffing load levels on the deck may already be greater than necessary and that the implementation of UAVs may afford additional decreases in the number of required crew on the flight deck.

THE SIMULATION ENVIRONMENT

The simulation environment used in this evaluation is part of the larger Deck operations Course of Action Planner (DCAP) system [11, 12]. The simulation environment is based on the current Nimitz-class (CVN-68) series of aircraft carriers [13]. The simulation environment (Figure 1) models the presence of aircraft, crew, ground vehicles and deck equipment, the latter of which includes elevators, arresting gear and launch catapults. The actions taken on deck and the expected times of execution are based on information obtained from a series of interviews with experienced crew from Naval Air Technical Training Command at Naval Air Station Pensacola. All task times (e.g. fueling rates and time to attach to catapult and launch) are modeled by Gaussian distributions with independently specified means and standard deviations.

Within the simulation environment, four major parameters can be varied (Table 1) – the crew included in the scenario (*Crew Complement*), the roster of aircraft included in the test scenario (*Aircraft Roster*), the ability of UAVs to perform tasks on the deck (*UAV Proficiency*) and the crew required for UAV taxi operations (*UAV Crew Requirements*). Details on these four parameters are discussed in the following sections.

Crew Complement

The number of crew present on the deck and the number of crewmembers from each crew class (Table 2) can be varied within the simulation. For this research, only a certain subset of the crew roster (Blue, Brown, Purple and Yellow crew classes) is allowed to vary. The numbers of Green, Red and White crewmembers are left unchanged due to their reliance on other factors – the required number of Green-jersey crew is driven by the manner in which catapults operate, Red-jerseyed crew by the manually-intensive nature of weapons loading and White in cover-

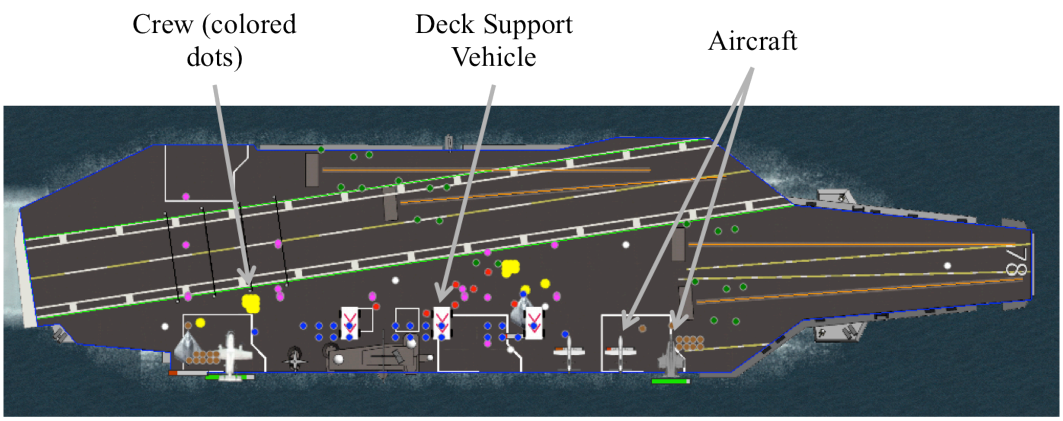

Figure 1. Screenshot of the DCAP Simulation environment

Table 1. Variable Parameters within the DCAP simulation.

Crew Complement	*Aircraft Roster*	*UAV Proficiency*	*UAV Crew Requirements*
• 100% (Full) to 25% complement, decreased in 5% increments	• All Manned • Half Manned/Half Unmanned (Mixed) • All Unmanned	• Slower than manned aircraft • Equivalent to manner aircraft • Faster than manned aircraft	• Equal to manned aircraft • Less than manned aircraft

Table 2. List of crew groups (by color) and roles.

Uniform Color	Role	Initial Complement	Variable?
Yellow	Escorts and guides aircraft on deck	20	✓
Brown	Oversees plane maintenance; aids in escorting aircraft on deck	20	✓
Blue	Responsible for deck equipment; aids in escorting aircraft on deck	24	✓
Purple	Responsible for fueling aircraft	20	✓
Red	Handles weapons loading and unloading	10	
Green	Operates catapult and landing strip arresting wires	20	
White	Safety officers – serve only a monitoring role	7	

ing the surface area of the deck for safety monitoring. The number of crew within each of the four remaining classes is allowed to vary with *Crew Complement,* but the relative ratios between the four classes is kept constant.

Aircraft Roster

Four generic aircraft models are used within the simulation, comprising all combinations of manned/unmanned and fast/slow vehicles (Table 4). In the testing scenarios used here, the *Aircraft Roster* was limited to twenty aircraft – the size of a single launch "Event." For this set of twenty aircraft, "Fast" vehicles comprise 75% of the air wing (16 vehicles) with "Slow" vehicles forming the remainder. Varying the *Aircraft Roster* parameter alters the ratio of unmanned to manned aircraft within the Fast/Slow categories (the rows in Table 4). For example, the All Manned setting would include 16 F-18s and 4 C-2s; the All UAV setting would include 16 Pegasus UAVs and 4 Predator UAVs. The Mixed setting would include an even split of each subcategory (e.g. 8 F-18s and 8 Pegasus).

UAV proficiency in task execution

Since there is no current estimate for precisely how well (or poorly) UAVs, such as UCAS and UCLASS, will perform on the carrier deck, both improvements and degradations in capabilities are modeled (Table 3). The "Slower" setting results in UAVs taxiing, turning and attaching to catapults at 75% the rate of a manned aircraft. "Faster" results in UAVs turning and attaching to catapults at 125% the speed of a manned aircraft. Taxi speed is not increased in the "Faster" setting as the maximum taxi speed is a hard constraint levied on all aircraft on the carrier deck and is not a function of vehicle capability. The third setting, "Equivalent," results in UAVs and manned aircraft performing tasks at identical rates.

The implementation of UAVs on the carrier deck brings with it no guarantees that unmanned vehicles will perform as well as manned aircraft in performing any task on the flight deck. Pending how UAV taxi operations are conducted, operations may be significantly slower and more problematic. Remote piloting of UAVs may introduce lags in the communication system, or operators may have difficulty viewing and understanding instructions from the crew. Gesture recognition technology, proposed as an alternative to remote piloting [14-17], is limited by the processing capabilities of the onboard systems. Furthermore, the speed of UAV operations may be artificially limited through safety constraints imposed by the crew, at least until such time as the UAVs have proven themselves to be of minimal danger to their human crewmembers.

Table 4. Types of aircraft modeled in the DCAP simulation.

	Fast (higher flight speed; requires weapons)	*Slow (lower flight speed; no weapons)*
Manned	Fast Manned Aircraft (FMAC, based on F18) Lowest endurance	Slow Manned Aircraft (SMAC, based on C2 Greyhound) High endurance
Unmanned	Fast UAV (FUAV, based on X-47B Pegasus) Medium endurance	Slow UAV (SUAV, based on the MQ-1 Predator) Highest endurance

Table 3. Variations in *UAV Proficiency* in the DCAP Simulation.

	Slower	*Equivalent*	*Faster*
Taxi Speed	75% of nominal	100% of nominal	100% or nominal (safety constraint)
Turn Rates			125% or nominal
Attachment to catapult			

However, automated systems have previously shown the ability to perform as well as, if not better than, human pilots. F-18 fighter jets currently have the capability to execute automatic landings at a highly proficient level [18], with the X-47B UAV having shown similar proficiency in recent testing [19]. Enhancements in the ability of UAVs to perform collision avoidance while in taxi [8, 20] in conjunction with automated route planning [21, 22] may allow for the creation and execution of more efficient and safer taxi operations for the aircraft and crew on deck, overcoming limitations imposed by remote piloting. Additionally, the implementation of various sensors on the aircraft and on deck equipment (akin to the work shown in [10]) may allow UAVs to operate with greater precision on the carrier deck[1].

UAV Crew Requirements

The implementation of UAVs on the carrier flight deck will also introduce changes in the methods of interaction between deck crew and UAVs. While the exact changes that may take place in crew interaction are not currently known, it is likely that increases in UAV autonomy will take the form of reduced interaction with crew during taxi operations. Currently, taxi operations are modeled such that manned aircraft require one Yellow-, one Brown- and two Blue-jerseyed crewmembers to be present[2]. Within the simulation, increasing the autonomy of UAVs reduces the number of required crew by half. The Brown-jerseyed Plane Captain, responsible for overseeing the aircraft when the

[1] In current operations, it is not uncommon for crew to manually push or pull a piloted aircraft into proper position on a catapult. High-fidelity sensors may allow for automated docking of UAVs to catapults, speeding operations by at least some degree.

[2] In reality, the required number and types of crew is highly variable and changes with a variety of conditions; the simulation implements a mid-range value at this time.

pilot is not present, may not be needed, as there is no pilot to replace. The two Blue-jerseyed crewmembers, which oversee chocks and chains and aid in a safety watch, may also not be needed if the aircraft (and all others) has sufficient collision avoidance capability. The remaining Yellow-jerseyed Aircraft Director is expected to remain present in some functional role, either providing gesture-based commands to the UAV, communicating through a handheld device, or some other form of instructional guidance.

METHODOLOGY

Two separate evaluations were performed, each utilizing different variations across the four parameters described in the previous section. In each case, the system begins with twenty aircraft parked on deck; all twenty will launch from the deck during the course of the simulation. Each parameter combination utilized within an evaluation is referred to as a single test scenario. Due to the stochastic nature of the simulation, each test scenario was executed ten different times to adequately capture variations in performance. Two main measurement metrics were tracked for each scenario – the time at which the last aircraft launched from the deck (Final Launch Time, FLT) and the total amount of time during which deck crewmembers were actively engaged in tasks (Total Crew Active Time, TCAT). The former is used as a measure of operational efficiency, the latter as a measure of crew workload and used to determine possible staffing reductions. If two test configurations demonstrate different TCAT values, the scenario with the lower value may afford reductions in staffing on the deck. However, increases in workload are not necessarily detrimental; if reducing the crew roster does not affect operational effectiveness and does not result in excessive crew workload, fewer crew may be needed for this deck configuration.

The first evaluation, **Crew Reduction Effects**, varied only the *Crew Roster* parameter and used only the All Manned *Aircraft Roster* setting. This evaluation aimed to determine the minimum staffing load required for maintaining operations. *Crew Roster* sizes were incrementally decreased from 100% to 25% in 5% increments. The minimum crew staffing level – defined as the smallest *Crew Roster* size before which mission efficiency begins to degrade – was calculated from this data and is used at the starting point for the second evaluation. The second evaluation, **UAV Effects on Minimum Crew Level**, varied all four simulation parameters and examined how increases in UAV autonomy and the relative number of UAVs on deck affected mission efficiency and crew workload at the minimum operational setting. The results of this evaluation will indicate whether additional force reduction may be possible on the flight deck. All scenario runs were performed on desktop computers running Ubuntu 10.04 LTS, with the DCAP Simulation Environment executed in the Eclipse Java™ IDE. Data was entered into SPSS™ for statistical analysis.

Results and Discussion

This section discusses the results of the two test evaluations independently, beginning with *Crew Reduction Effects*.

Effects of Crew Reduction

This first evaluation examined the effects of crew roster size on operational efficiency and crew workload for current operations involving only manned aircraft. This analysis varied only the *Crew Roster* parameter from the full complement to a final value of one quarter of the original crew. The minimum crew roster setting, where further reductions in crew roster size begin to elicit degradations in operational performance, can then be determined from the data set. The resulting values of Final Launch Time and Total Crew Active Time for this evaluation are found in Figure 2 and Figure 3, respectively.

Figure 2 indicates that Final Launch Time (FLT) values begin to increase at the 45% roster size. An omnibus ANOVA test at $\alpha = 0.05$ reveals no statistical differences in FLT for the 100% to 50% *Crew Roster* settings ($p = 0.312$), while statistical differences were seen between the 50% and 45% settings (ANOVA, $p = 0.000$). From 45% crew roster size and decreasing, mission duration continues to increase. Given this information, the 50% *Crew Roster* setting is designated as the minimum crew setting for this test scenario and will form the starting point for the second evaluation.

The trend observed in FLT may be explained by limitations in the availability of specific crew classes on the deck. The dynamics of deck activity allow up to three aircraft to queue at one of the three available catapults on the deck (a fourth is unavailable). Within this test scenario, a minimum of 12 Blue-jerseyed crew (3 catapults x 2 queue spots x 2 Blue crew required) and 6 Yellow- and Brown-jerseyed crew (3 x 2 x 1 crew required) are required to maintain a minimum queue size of 2 aircraft per catapult. Once this threshold is breached at the 45% crew roster setting (now less than 12 Blue crew), catapults may sit idly – operational, but without aircraft currently launching or in queue to launch. FLT suffers as a result of this and continues to degrade as additional crew are removed.

Figure 3 shows the results for Total Crew Active Time from this same data set. In this case, however, crew workload begins to increase immediately and continues to do so until the roster size decreases to 75%. From this point forward, TCAT remains within +/- 4 minutes of the median value at the 75% roster size. Also, note that the variation between the minimum and maximum crew workload levels – a total of 15 minutes – is distributed across all crewmembers.

The break point that occurs at the 75% roster size may also be a function of the number of Blue crew on deck. At the 75% crew setting there are sufficient Blue crew (18) to maintain three aircraft in each catapult queue (3 catapults x 3 queue spots x 2 Blue crew required). At crew roster sizes above this value, enough crew wait idly on deck that a crew member is always readily available. At 75% crew roster size and below, crew are immediately assigned a new task after completing their current task; aircraft may also be forced to wait for these personnel. This places at least a subset of the escort crew in a continual state of activity with nearly zero idle time. As crew numbers are further reduced, this state of

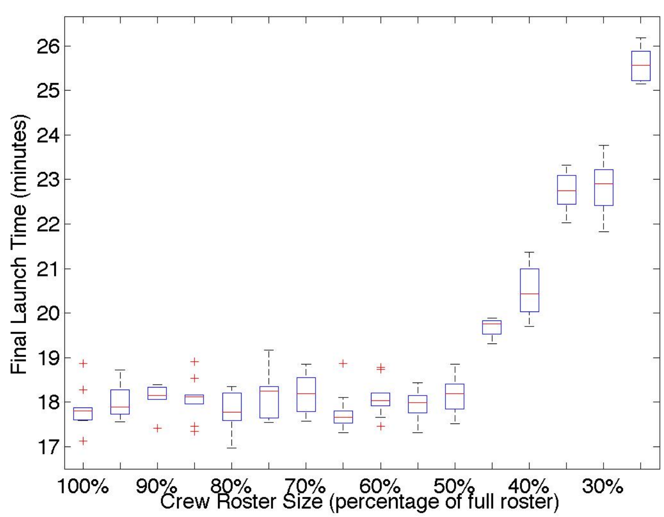

Figure 2. Final Launch Times for Manned Only roster with varying crew roster sizes.

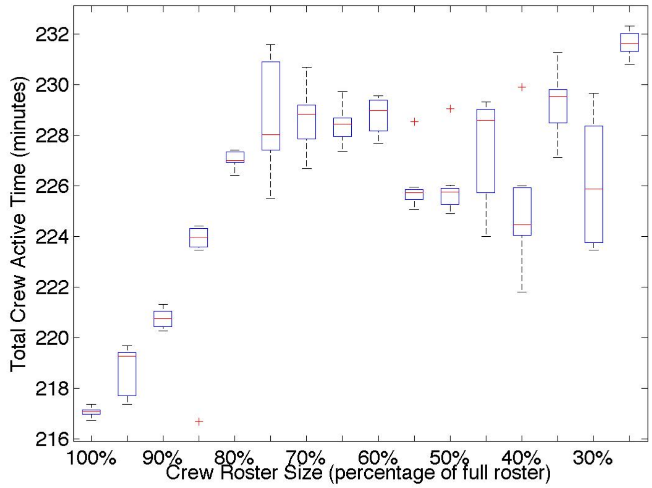

Figure 3. Total Crew Activity for Manned Only roster with varying crew roster sizes.

constant activity does not change; what does change is the nature in which tasks occur. With larger numbers of crew, tasks may occur in parallel. As the number of crew decreases (eventually to only one set of escort crew) activities begin to occur in series. The same amount of labor is being performed, leaving TCAT somewhat constant, but the increasingly serial nature of tasks leads to continued increases in FLT.

UAV Effects on Minimum Crew Level

The first evaluation revealed that current staffing levels on the deck may already be higher than needed; this second evaluation examines whether additional reductions in the number of crew can be obtained through increasing levels of UAV autonomy. This evaluation varies all four parameters – *UAV Proficiency* (Equivalent and Faster), *UAV Crew Required* (Equivalent and Less), *Aircraft Roster* (All Manned, Mixed and All Unmanned) and *Crew Roster* (50%, 45%, 40%). In this case, only options that suggested increased mission efficiency or staffing reductions were kept. The 50% *Crew Roster* setting was used as the initial investigation point, with two additional settings added for additional resolution. This resulted in a total of twenty-one test scenarios, seven at each of three *Crew Roster* settings.

FLT values for the 50% case showed no statistical differences in an omnibus Mann-Whitney U Test ($p = 0.219$). This led to the addition of two additional cases at the 45% and 40% crew roster settings. The 45% *Crew Roster* setting also showed no statistical differences in an omnibus Mann-Whitney U test ($p = 0.079$), while the 40% crew roster setting (Figure 5), found statistical differences for two of the seven cases – the Mixed/UAV Faster/Less Crew case and the All UAV/Faster/Less Crew case (data sets D and G). While these two data sets are statistically different, they are not all that dissimilar from the remaining five data sets, which were statistically equivalent in an omnibus Mann-Whitney U Test ($p = 0.201$).

Values for TCAT, however, did show statistically significant variation between scenarios at all three *Crew Roster* settings, primarily driven by the *UAV Crew Requirements* parameter. Figure 4 shows the data from testing at the 40% crew roster. For a given *Aircraft Roster* setting, only cases where *UAV Crew Requirements* were set to the "Less Crew" setting showed statistically significant differences in TCAT. For scenarios where only *UAV Proficiency* was altered (data sets B and E), values were not statistically different from the All Manned baseline (data set

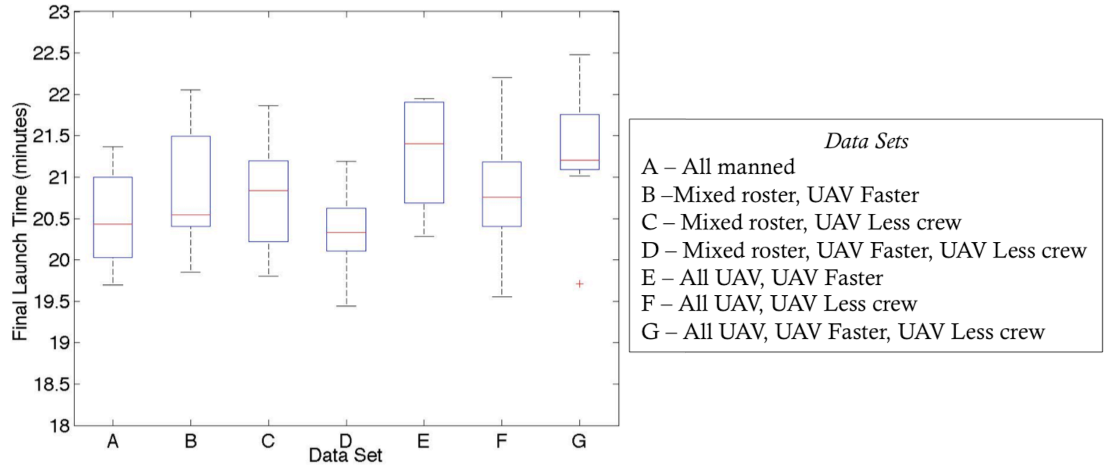

Figure 5. FLT values for the 40% *Crew Roster* complement

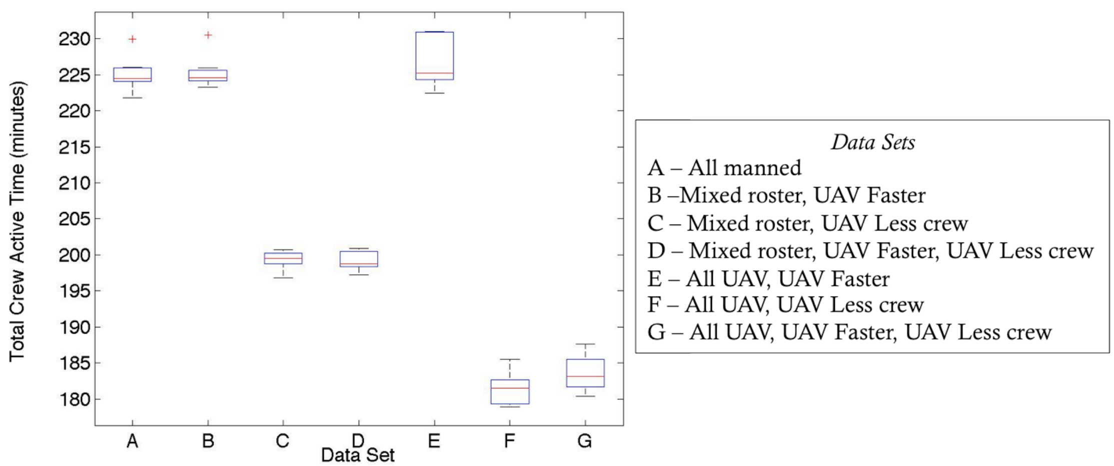

Figure 4. TCAT Values for the 40% *Crew Roster* complement.

A). For cases in which both of these settings were varied (data sets D and G), values of TCAT were not statistically different from those where only *UAV Crew Requirements* had been altered (data sets C and F). Interestingly, this suggests that increasing the technical proficiency of UAVs provides no benefit to the system overall and that there are also no combinatorial effects regarding *UAV Crew Requirements* and *UAV Proficiency.*

Conclusions

The data discussed in the previous sections suggest several important points concerning current and future aircraft carrier operations. For current operations, the first evaluation (the Crew Reduction Effects) suggests that the flight deck may currently be overstaffed, as evidenced by the trends for both FLT and TCAT. For future operations involving UAVs, potential increases in vehicle efficiency may not generate increases in mission efficiency. This latter point may likely be a factor of the limited nature with which UAV proficiency can be increased and may also be influenced by the fact that the scenarios tested here dealt only with the nominal operating case for a single launch Event. Other scenarios that provide a longer window of operations – for instance, multiple launch Events up to a full day of operation – or that test the ability of the system to recover from failures may show beneficial effects of increased UAV proficiency levels. Additionally, it may be that current taxi and launch procedures are already near optimal, with little additional gain possible.

Interestingly, at the minimum crew roster level, the implementation of highly-autonomous UAV capabilities (requiring fewer crew in taxi operations) did not further increase mission efficiency. The effects seen in the first evaluation (**Effects of Crew Reduction**) showed that FLT was primarily driven by the number of Blue-jerseyed crew available on the deck; even though the required number of these crew was halved for UAVs in the second evaluation (**Effects of UAVs on Minimum Crew Level**), no further increase in mission effectiveness was seen. This increased autonomy did create significant effects in terms of crew workload, however, with the greatest reduction occurring for the pair of All UAV/Less Crew scenario. At this time, a second examination of crew roster sizes for this configuration has not been calculated and thus the maximum crew reduction afforded by this configuration is not currently known.

Two additional benefits of UAV implementation also exist but were not explored in this testing program. Firstly, the UAVs modeled within the DCAP simulation environment use substantially less fuel than their manned counterparts. As such, the total time to fuel aircraft from an empty state will be markedly shorter for an air wing with a large UAV component. However, this is not directly a function of UAV autonomous capabilities and thus was not explored in this work. Secondly, inherent in the definition of a UAV is the removal of the human pilot from the aircraft, which may allow further reductions in staffing given the level of autonomy with which the vehicle behaves. For instance, the remotely piloted MQ-1 Predator exhibits minimal autonomy and requires three controllers (at minimum) to execute operations. Without additional reductions in crew staffing, adding Predator UAVs to the flight deck would result in a net *gain* in crew staffing. The X-47B Pegasus, however, is being designed to execute task-based controls, which could allow single operators to control multiple vehicles at a time [23]. Even if the system is not explicitly single operator-multi UAV control (for instance, two controllers managing four UAVs), controller-to-vehicle ratios of less than one will result in at least some level of force reduction.

There are also a variety of limitations in this work that should be addressed in the future. A major factor in these results is that a single launch event of 20 aircraft was modeled (rather than a full complement of 40-60 aircraft) with no major failures on deck. It is likely that the level of overstaffing suggested by this research is beneficial primarily for off-nominal, outlier cases. For instance, for an aircraft crashing on landing, a larger crew roster may allow debris to cleared, the aircraft to be moved and the deck reset for landing at a faster rate than the minimum staffing level found here. Concerning modeling of the individual crew and the crew roster, two limitations exist. The first concerns how the crew were modeled; in this testing, the crew classes were scaled at the same rate, leaving the ratios between crew groups constant. As shown in the second evaluation, degradations in mission efficiency were due primarily to a single crew group (Blue). Further reductions may be achievable by investigating the minimum staffing level for each independent crew class, then aggregating these minimum staffing levels into a single roster. Secondly, limitations in the ability to observe and catalogue actual flight deck operations and the lack of access to official records and detailed logs of operations have hindered the development of the simulation environment in general. Although examined by numerous subject matter experts, a much higher level of accuracy and fidelity could be achieved. Specifically in regards to crew modeling, modeling delays in crewmembers recognizing tasks, crew wandering into “foul areas”, and better modeling of human interaction with the various aircraft could be implemented.

However, despite these limitations, these results suggest the possibility that the current staffing load on the deck is in excess of what is needed and that the greatest influence of UAV autonomy on force reduction efforts lies in reducing the number of crew required to explicitly interact with these vehicles, not in achieving more efficient vehicle performance. Increases in UAV performance provided no substantial benefits to operations; however, designing the vehicles to exhibit at least comparable performance to manned aircraft should preserve the current level of system performance. Numerous issues remain to be examined in how off-nominal and outlier cases affect staffing requirements on the deck and may demonstrate that for these cases, force reductions may not be possible without compromising mission effectiveness and crew workload.

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