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Feasibility Study of Global-Positioning-System-Based Aircraft-Carrier Flight-Deck Persistent Monitoring System

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This research analyzes the use of modern guidance, navigation, and control concepts, such as the Global Positioning System, with the potential for improvements in the safety of aircraft, equipment, and personnel onboard a U.S. Navy aircraft carrier. The results of a detailed analysis of U.S. Navy safety records since 1980 show that mishaps that could potentially be prevented by a persistent monitoring system have resulted in the deaths of 13 sailors and account for over $90 million in damages, or 5% of the total cost of all flight-deck- and hangar-bay-related mishaps. Research efforts included a study of the movements of U.S. Navy personnel and an FA-18C aircraft being towed at Naval Air Station Oceana, Virginia. Pseudospectral motion planning techniques are explored to provide route prediction for aircraft, support equipment, and personnel. A system to continually monitor flight-deck operations is proposed, with four successive levels of increasing capability. The research shows that radio navigation can provide the necessary accuracy to improve flight-deck safety, but that substantial computing power and augmentation of the Global Positioning System are necessary.

I. Introduction

THE flight deck of a U.S. Navy (USN) aircraft carrier (CV, CVN), depicted in Fig. 1, is an inherently dangerous place to work. An embarked carrier air wing (CVW), usually composed of around 64 aircraft, must perform all of its flight-deck operations using only 4.5 acres of flight-deck space. These close quarters, combined with the rapid pace of flight-deck operations and the dangers faced by any oceangoing vessel, create conditions that are among the most dangerous in the world. The official USN records of flight-deck mishaps [1] include many serious injuries and fatalities, as well as numerous instances of damage to or loss of aircraft.

After examining 29 years of flight-deck-related mishap records, provided by the Naval Safety Center, this research develops a new mishap classification system. Rather than classifying mishaps by cost, a new system is proposed to group mishaps by cause. New methods and systems to mitigate the risks that contribute to these mishaps are proposed. This research will focus exclusively on the CV/CVN class of aircraft carrier, although many aspects may be applicable to the smaller amphibious assault vessels. A full description of the operations onboard an aircraft carrier is beyond the scope of this document. A brief introduction to flight-deck operations is provided in [2].

This section provides an examination of safety records as problem motivation and introduces the concept of a persistent monitoring system for the flight deck and hangar bay of aircraft carriers. Section IV explores areas of prior research related to this study. The data collection methods for this research are discussed in Sec. V. Results are presented in Sec. VI, with conclusions in Sec. VIII.

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II. Safety Records

This section examines the data provided by the Naval Safety Center, available under the Freedom of Information Act, on all reported mishaps involving an aircraft carrier from 1980 through 2008. These data include 3228 mishaps, both airborne and onboard a ship. Only 1506 of the mishaps provided have a narrative, or description, of the mishap. The narratives are required to determine the appropriate grouping for the event. The mishaps without narratives require privileged access, which could not be provided for this study. Therefore, only the 1506 mishaps with narratives were evaluated in this study. As the severity of the 1722 mishaps without narratives is unknown, the potential for bias resulting from their exclusion cannot be discounted.

A. Mishap Classification

Before examining the data further, it is important to discuss how they are collected. For any aviation-related mishap resulting in injury to personnel or damage to equipment, the squadron or organization responsible must submit either a hazard report (HAZREP) or mishap data report (MDR). The purpose of the HAZREP or MDR is to record objective data for analysis by the Naval Safety Center, but there are numerous reasons why the data contained in the report may not reflect the totality of reality. Because of the natural desire to downplay the significance of a mishap and the amount of damage, as well as the inherent difficulty in capturing the true total cost of a mishap, the estimated cost is typically much lower than one would expect.

The Naval Aviation Safety Program [3] classifies mishaps based upon the number of workdays lost due to injury or the financial severity of damage to equipment. Mishaps are also categorized as flight, flight-related, or aviation ground mishaps; but, for the purposes of this research, these distinctions are not sufficient. According to the instructions for this program, a mishap is categorized as flight or flight-related if the intent for flight existed, not simply if it occurs in the air. A collision between a sailor or parked aircraft and an aircraft launching from a catapult is reported as a flight mishap, but it is still of interest to this research, because it is potentially preventable. On the other hand, a mishap caused by system failure on the aircraft during launch, also reported as a flight mishap, is outside the scope of this research.

The severity of a mishap is classified by assigning a letter designator, based upon cost. The process of determining the cost of a mishap is detailed in section 314 of the Naval Aviation Safety

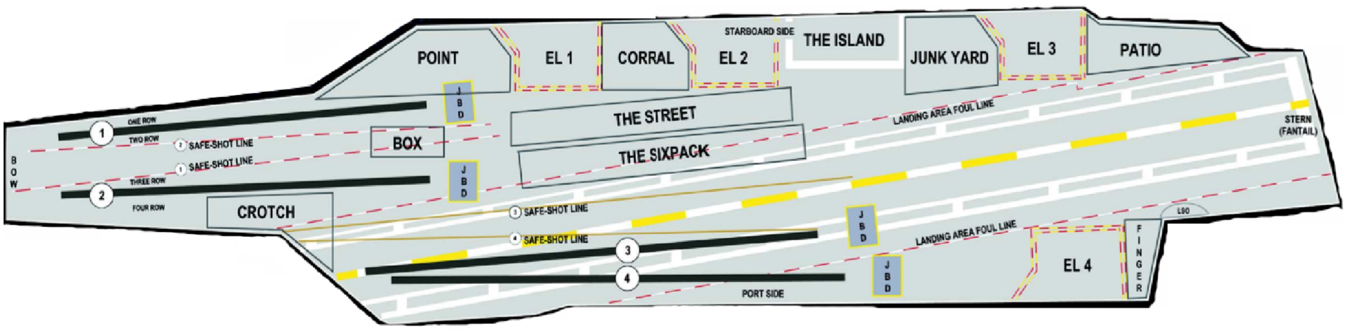


Fig. 1 Diagram of modern aircraft carrier (CV/CVN) flight deck [2]: EL denotes the location of one of four elevators, and a circled number over a long black line provides the location and identification of each catapult.

Program [3]. The reporting organization is directed to, "Compute the cost of damage to DoD property, using the best known cost of repair or replacement. Base these cost estimates on the price of materials and man hours necessary to repair the damage."

Even more important than the cost associated with a mishap is the impact it has on the CVW's mission. The collision of two aircraft on the flight deck can lead to the loss of scheduled sorties, delays in the scheduled maintenance of other aircraft, and increased strain on the logistics train. The effect of one mishap is typically felt for days or weeks, as schedules are adjusted, with the result being a reduction in the ability to provide striking power from the sea.

Because the focus of this research is to evaluate methods to reduce or prevent mishaps, it is necessary to group mishaps into categories based upon causes, not costs, so that the causes can be targeted for mitigation. The next step is to evaluate the causes of the mishaps in each category and research technological improvements that could be leveraged in an attempt to reduce their occurrence. A set of categories were created that describe all of the flight-deck-related mishaps that could potentially be prevented by modern guidance, navigation, and control (GNC) technologies. If a narrative in the mishap reports described a mishap that the authors thought was potentially preventable, it was marked an interest mishap. Based upon the events described in the narratives of interest mishaps, the following categories were created.

1) The spotting category applies to when aircraft is stationary when another object in its normal operation impacts it, or aircraft begins uncontrolled movement due to the ship's motion. (Note that, if an aircraft is towed into another aircraft, it is considered a towing mishap, regardless of the position of the stationary aircraft.)

2) The towing category applies when, while under tow, an aircraft or tow tractor collides with a (nonhuman) object. This classification also covers aircraft being pushed into a parking position.

3) The taxiing category applies when, with a pilot in command, an aircraft collides with a (nonhuman) object.

4) The exhaust category applies when an aircraft is damaged or a sailor is injured by engine exhaust.

5) The contact category applies when a sailor is injured or killed by contact with a moving aircraft (excludes engine/exhaust contact).

Table 1 Occurrence and average cost of mishap categories: occurrence given as percent of total mishaps with narratives (excluding HAZREPs)

Category	Occurrence, %	Mean reported cost, $
Spotting	5.19	1,251,800
Towing	10.71	335,800
Taxiing	8.93	319,100
Exhaust	5.03	181,000
Contact	4.06	83,800
Engine	1.46	60,600
Wing fold	0.32	10,900
Nonaviation	0.16	1,200
Miscellaneous	2.44	39,800
Unknown	1.79	906,100

6) The engine category applies when an aircraft is damaged or a sailor is injured by contact with a turning engine (usually the propeller).

7) The wing-fold category applies when the spreading (or folding) of an aircraft's wings impacts another object, typically another aircraft.

8) The nonaviation category applies when an aircraft is damaged during a nonaviation-related event, such as an underway replenishment.

Secondary categories include the following.

1) The miscellaneous category applies to any flight-deck or hangar-bay mishap that does not fall into the above categories but may still be potentially preventable.

2) The unknown category applies when some mishap, that could potentially be prevented, occurred on the flight deck or hangar bay, but the exact circumstances cannot be determined from the available information.

The occurrence and mean cost[‡] of these categories is presented in Table 1. To further illustrate the method by which mishaps were classified based upon their narrative, an example for each of the primary categories is provided in Table 2.

B. Mishap Data Analysis

Figure 2 illustrates the trends in mishap occurrence during the period of time covered by the available data. Total mishaps include every mishap within the available data,[§] including airborne mishaps and HAZREPs. It is interesting to observe that, in more recent years, the interest mishaps constitute a larger percentage of the total. The primary reason for this is that the more recent data have a larger percentage with narratives. If narrative data were available for a larger percentage of earlier mishaps, it is likely that interest mishaps would constitute a much larger percentage of the overall total.

There are 1373 HAZREPs in the data provided by the Naval Safety Center, with a total reported cost of only $750, the vast majority having a reported cost of $0. Removing these from the evaluation shows that interest mishaps make up a larger portion of each year's totals than is depicted when they are present.

The total cost of interest mishaps since 1980 is $92,486,469: 5.55% of the cost of all recorded mishaps in these data (including those lacking narratives). The purchase cost of an FA-18(E-F) aircraft is $43.6 million [4]. This should provide significant motivation to explore a means of reducing aircraft-related mishaps.

From the 261 interest mishaps, there are 13 fatalities and 34 major injuries. The major injuries counted involved sailors being run over by an aircraft, ingested into a turning engine, or being blown overboard. These numbers were generated from reading the brief narratives, which do not always expressly state the severity of the

[‡]Cost data used in this research are unchanged from the data provided. As an example, adjustments for inflation are not made. This is consistent with Naval Safety Center practices.

[§]Few mishaps are listed for fiscal year 2008, as the data were provided early in the fall of 2007. They are included in this analysis for the sake of thoroughness.

Table 2 Examples of mishap narratives and their classifications: narratives are presented exactly as recorded by Naval Safety Center.[a]

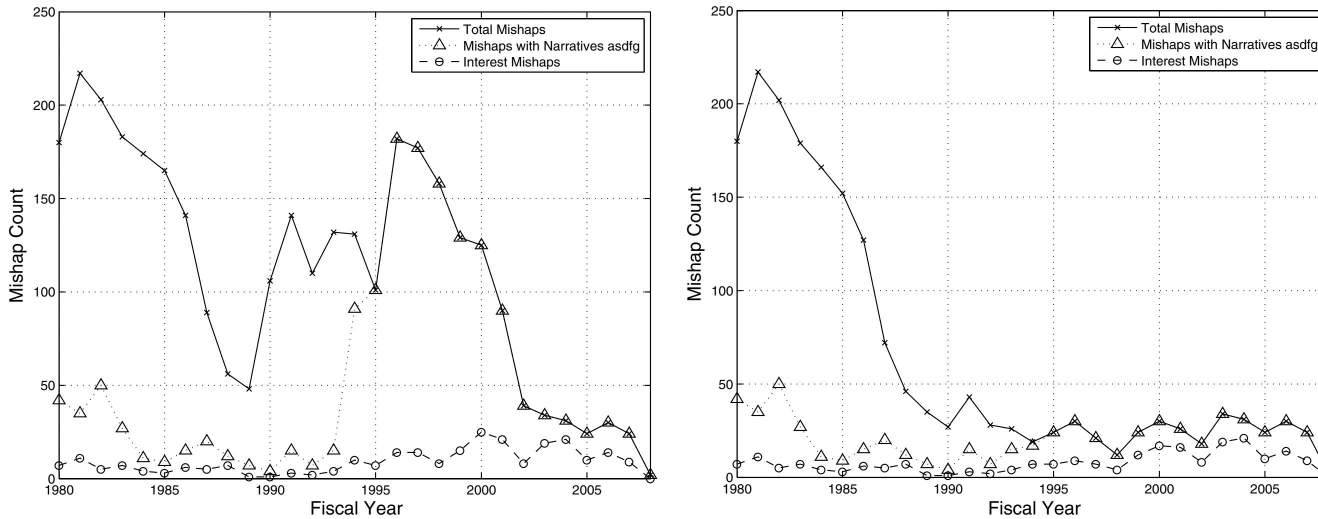
Event serial	Fiscal year	Narrative	Classification
22273	1986	PARKED ACFT SUSTAINED DAMAGE WHEN BARRICADE STANCHION STRCK HORIZ. STAB	Spotting
40688	1994	ACFT UNDER TOW IN HANGAR DECK BAY COLLIDED WITH PARKED ACFT.	Towing
47673	1998	ACFT RADOME IMPACTED BY AILERON OF SECOND ACFT WHICH WAS TAXIING ON DK	Taxiing
53357	2001	FLIGHT SURGEON BLOWN OVERBOARD DURING CQ OPERATIONS	Exhaust
35370	1992	BLUE SHIRT RUN OVER BY ACFT MAIN MOUNT	Contact
47642	1998	PLANE CAPTAIN STRUCK BY TURNING PROPELLER	Engine
50548	2000	UNCOMMANDED WING SPREAD CAUSED WINGS TO STRIKE ACFT IN CLOSE PROXIMITY	Wing fold
69377	2006	ACFT PARKED ON FLT DECK STRUCK BY FORK LIFT TRACTOR DUR REPLENISHMENT.	Nonaviation

[a]ACFT denotes aircraft, STRK denotes struck, FLT denotes flight, DUR denotes during, DK denotes deck, and CQ denotes carrier qualifications.

injury. A fatality was only recorded if the narrative expressly said the sailor was killed. Figure 3 shows the number and recorded costs of fatalities and major injuries.

C. Conclusions from Safety Records

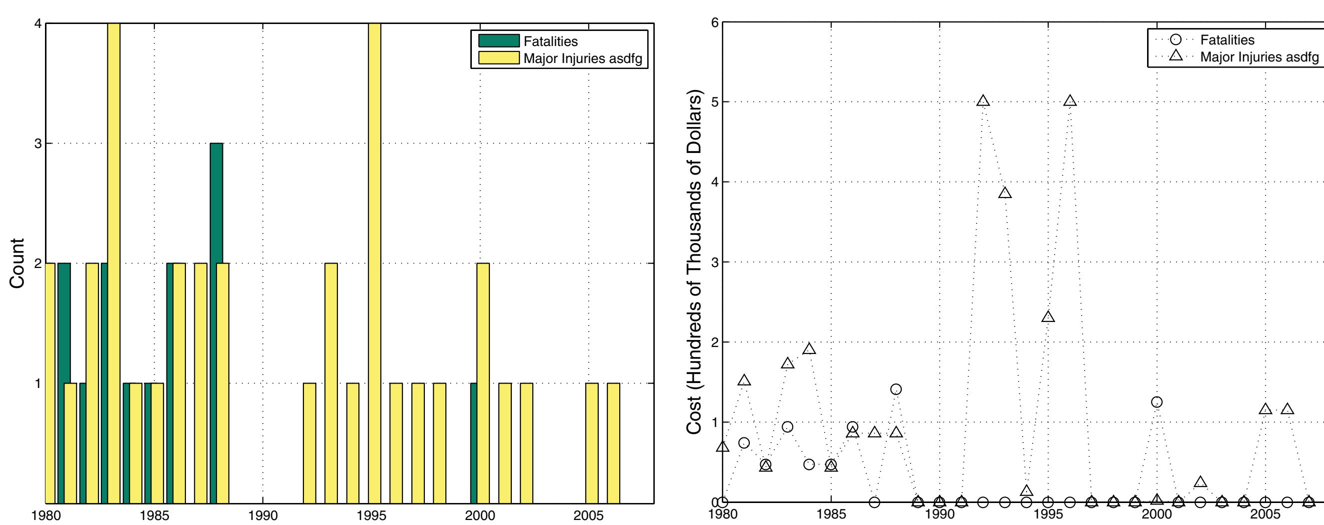
With the improvements in flight safety over the last decade, mishaps occurring on the flight deck of an aircraft carrier are taking an increasing share of each year's total mishap cost. The annual cost of interest mishaps is consistently in the $2–4 million range. By closely examining the data reported to the Naval Safety Center, it has been shown that potentially preventable mishaps (and their costs) make up a significant percentage of the total each year. This mishap cost analysis was performed to show that there is still a significant cost every year to the USN for mishaps that have been identified as potentially preventable.



a) Number of all Mishap and Hazard reports by year

b) Number of all Mishaps by year (excludes Hazard reports)

Fig. 2 Number of all mishaps by year.



a) Number of fatalities/major injuries

b) Cost of fatalities/major injuries

Fig. 3 Injuries and fatalities from interest mishaps.

III. Persistent Monitoring

To prevent mishaps from occurring, it is necessary to provide key personnel with more accurate and timely data, describing the state of all aircraft, equipment, and personnel on the flight deck and in the hangar bay. To do this, a system must first be developed to more accurately estimate the aircraft position, orientation, and velocity than is currently done. The purpose of a persistent monitoring system is to measure the flight-deck state. Once these data are collected, they could be applied to hazard mitigation or more efficient management.

Since the creation of carrier-based aviation, the management of the carrier flight deck has been an extremely challenging task requiring hundreds of personnel, each having years of experience. The current system has changed very little since the 1950s. Personnel on the flight deck use hand signals to communicate with each other and direct the pilot to make aircraft control system inputs. The position and orientation of each aircraft is loosely monitored in flight-deck control by placing objects representing aircraft on a table, commonly referred to as the Ouija board, in their estimated positions and orientations.

When towing an aircraft, wing and tail safeties are used to ensure the towed aircraft does not impact another, while the driver of the tow tractor ensures the route is clear of obstructions. Currently, the state of each aircraft (position, orientation, and translational/rotational velocities) is estimated by only a human observer's judgement.

This research supposes that it is this approach to measuring the flight-deck state, based on human estimation, that creates a potential for mishaps. With a very large quantity of aircraft, support equipment (SE), and personnel, as well as flight-deck surfaces [such as jet blast deflectors (JBDs), elevators, and catapults], the flight deck has more state variables than humans can continually observe. A computer-based tracking system, using modern GNC concepts, can continually monitor these variables much more accurately and consistently. For the purposes of this research, the fidelity with which such a system can determine the state will be divided into four levels based upon the capabilities the system would provide, increased expected difficulty, and cost of implementation. Each successive level will include the capabilities of all previous levels.

A. Level One: Aircraft

The purpose of a level one observation system is to reduce or eliminate spotting and taxiing mishaps. As previously stated, the position, orientation, and translational/rotational velocities of aircraft on the flight deck are currently determined by only visual estimation. To improve this, a new computer-based system can be developed that provides measurements of the aircraft state in near real time to flight-deck control or other systems and personnel concerned. Level one would also need to determine the status of flight-deck surfaces, such as the elevation angle of a JBD or the location of an elevator. Many different types of real-time locating systems (RTLS) could be leveraged to acquire these data, including radio locating systems and optical scanning.

B. Level Two: Support Equipment

A level two system adds the ability to reduce or eliminate towing mishaps and to further reduce spotting mishaps. Many mishaps with collision damage to aircraft involve SE, whether it is a tow tractor, a fire truck, a power generator, or a forklift. With a system that can determine the instantaneous position, orientation, and translational/rotational velocities of SE, it would be possible to reduce the occurrence of many spotting, towing, and nonaviation mishaps. For much of the larger SE, this could be achieved with a system similar to that used for level one, but many smaller items of SE, such as weapon carts, may require different treatment.

C. Level Three: Personnel

To improve the safety of flight-deck operations for individual sailors, it would be beneficial to determine their instantaneous position and velocity relative to hazards caused by aircraft, SE, elevators, JBDs, and exhaust plumes. With the rapid, relatively erratic motion of personnel on deck, as well as the requirement for close proximity to the aircraft to perform many critical tasks, the detection of a potential mishap involving personnel could be the most difficult to determine. Such a system could serve to mitigate contact mishaps and reduce the number of flight-deck casualties. It is expected that personnel tracking would only occur on the flight deck and in the hangar bay.

D. Level Four: Aircraft System Status

Many engine, exhaust, and wing-fold mishaps could be prevented by remotely monitoring an aircraft's throttle or wing-fold status. Using a data link to report necessary aircraft status information to flight-deck control could provide this capability. There are current systems that provide this information when the aircraft are powered, but it could prove beneficial to transmit this information when unpowered.

E. Benefits of Persistent Monitoring

Beyond the potential reduction in mishaps, there are many additional, significant benefits to a persistent monitoring system. Such a system could ease the integration of unmanned aerial vehicles (UAVs) into the CVW. The persistent monitoring system would track all vehicles, manned and unmanned, and could provide a flight-deck map to unmanned systems. This could allow UAVs to plan a path to their designated position around obstacles, such as personnel and other aircraft.

A persistent monitoring system could provide all levels of naval leadership with accurate recordings of all flight-deck activity. The current reporting system for mishaps does not document near mishaps, or those which were narrowly averted. Recording and reporting near mishaps could become the primary mechanism in reducing potential mishaps. Close calls occur frequently and, if recorded and reported, they could contribute to preventing mishaps through changes in policy, training, and modifications to the hazard identification algorithms. A complete recording of flight-deck activity would provide the Naval Safety Center with significantly improved documentation on the hazards of flight-deck operations, especially for forensic analysis. It would also provide commanders with detailed records of personnel actions that can be used to document training and experience, as well as justify manpower requirements.

IV. Related Work

This section discusses topics related to the development of a persistent monitoring system. Past and prior research efforts in the area of aircraft-carrier flight-deck modernization, as well as UAV incorporation, are presented. Path planning is discussed, as it could be used in hazard recognition. The kinematics of an articulated vehicle, such as a towed aircraft system, as well as the USN's aircraft towing procedures, are presented.

A. Flight-Deck Systems

Studies of methods to improve the communication of flight-deck state to flight-deck control and other personnel concerned for man-in-the-loop control were performed at the Naval Postgraduate School from 1974 to 1975 [5,6], the only open literature found on the subject. These studies did not incorporate RTLS, as precise positioning technology was just being developed.

In 1966, a report was published about the carrier aircraft deck operation control system (CADOCS) [7]. This is the first description of an attempt at using computer systems to improve flight-deck operations. It argued that, since many flight-deck management operations are repetitive in nature, they can be performed by a computer. It recognized that the quality of a solution provided by the computer is dependent upon the quality of the data it is provided. A variety of stationary and handheld devices used by flight-deck personnel were recommended for data entry.

The CADOCS concept was further refined in 1967 by King [8]. A system actually capable of generating the aircraft spotting plan for the entire flight deck, based upon maintenance status and flight schedule requirements, was proposed. Two of the unfavorable aspects of CADOCS described by Giardina are inaccuracy of position data and performance of existing computers [5]. The CADOCS system was further refined in two additional reports [9,10].

A system currently installed on CVNs, the Aviation Data Management and Control System, provides systems to track the flight schedule, as well as visual records of launch and recovery operations. The block 3 upgrade, scheduled for installation on U.S.S. Abraham Lincoln (CVN 72) in fiscal year 2010, will provide an automated, digital Ouija board. Measurements of aircraft position and orientation will be made by video analysis software. Expected accuracies of aircraft position measurements are approximately 0.3 m.

B. Carrier-Based Unmanned Aerial Vehicles

The problem of UAV incorporation on the flight deck is currently being actively pursued by many programs. The Unmanned Combat Aircraft System—Carrier Demonstration is a UAV prototype to demonstrate aircraft-carrier landing and recovery capabilities. The contract was awarded in August 2007, with a carrier landing attempt planned for 2012 [11]. The method of providing positive control during flight-deck operations is left to the vendor [12].

Venetsky et al. [13] performed an extensive study on the use of gesture recognition to enable UAVs to follow the directions of taxi directors, as pilots are trained to do. Each UAV would have a visual sensor mounted on it to watch its assigned director. There are significant obstacles, such as low light, light-source blooming, sun glare, steam, occlusion, and clutter. The results of the study are that such a system is feasible if visibility of taxi directors is augmented, sensors are placed high on the aircraft, and taxi director practices are more standardized.

C. Path Planning

The focus of much path-planning research is in the area of robotics. Areas of focus include wheeled mobile robots [14] and UAVs [15]. An edge following method is used by the Strategic-Tactical-Execution Software Control Architecture created by Fox et al. [16]. Other approaches use probabilistic knowledge of hazardous areas [17] or pick control inputs at random [18]. Extensive research has been conducted to determine the optimal, or near optimal, path for vehicular travel [15,19].

One of the best known path-planning algorithms, introduced by Stentz in [20], is known as D^*. The path generated by D^* will have the minimum cost associated with its traverse. This cost can be defined in virtually any manner; travel time, fuel consumption, and route distance are all valid components of cost.

A similar approach to the path-planning problem, solving for the optimal path and the associated controls based upon vehicle dynamics, is proposed by Gong et al. [21] and Lewis et al. [22]. This method allows obstacles to be of arbitrary size, number, and shape. It approaches the path-planning problem as a constrained nonlinear optimal control problem and solves it using pseudospectral computational methods [22]. Ross [23] have developed a MATLAB toolbox, called DIDO, to determine the optimal path for a given scenario.¶

DIDO allows for the computation of an optimal state trajectory through an n-dimensional state space. The states are not limited to location on a Cartesian plane but can be any parameters used to describe the configuration of a dynamic system: angles, quaternions, energy levels, etc. [23]. Given the dynamics of the states, DIDO minimizes a cost function $J(\mathbf{x},\mathbf{u},t)$, such that $h_i(\mathbf{x}) > 0$, where $\mathbf{x}$, $\mathbf{u}$, and t represent the states, inputs, and time, respectively. For the two-dimensional translational motion problem with states $x(t)$ and $y(t)$, Ross [23] represents an obstacle by [24]

$$h_i[x(t), y(t)] = \ln\left[\left|\left(\frac{x(t)-x_o}{a}\right)^p\right| + \left|\left(\frac{y(t)-y_o}{b}\right)^p\right|\right] \tag{1}$$

¶Data available online at http:www.elissar.biz [retrieved 8 December 2008].

where x_o and y_o are the center location of the obstacle, a and b are its width and height, and p determines its shape. For $p = 1$, the resulting obstacle is a diamond, $p = 2$ yields a circle, and $p = \infty$ results in a square [25]. Any point outside of the obstacle areas will have a value of $h > 0$ [22].

D. Articulated Vehicle Kinematics

When an aircraft is taxiing, the motive force is provided by engine thrust, and its direction is controlled by the angle of the nose wheel. Similarly, a tow tractor is propelled by the rear axle, and its direction of travel is controlled by the forward wheel turn angle. The kinematics of each of these vehicles can be represented as a tricycle, with a velocity input applied at the rear axle and a nose wheel angle input to provide heading control. It is assumed that the wheels roll without slipping, to provide a nonholonomic constraint. This kinematic representation allows the aircraft's motion to be analyzed without a need for the analysis of thrust levels, frictional forces, or inertial properties.

The study of the control of articulated vehicles requires an understanding of their kinematics. There are numerous areas of research using articulated vehicle kinematics. Ng et al. propose a vehicle following system using a virtual trailer link [26]. Bolzern et al. have performed extensive studies of articulated vehicles with offaxle hitching [27] and n-body articulated vehicles [28], where the independent variable is distance traveled. Larsson et al. propose a nonlinear state-space representation of a two-body system (a tractor and one trailer) [29]. The two-body system is insufficient to represent the towed aircraft system ashore, as a tow bar is used. Onboard an aircraft carrier, towing is often performed by a tow tractor that attaches directly to the nose wheel, creating a two-body system. Park et al. propose a kinematic representation of an n-body articulated vehicle, with time as the independent variable [30]. Using and adapting this representation allows for the development of kinematics to represent the three-body articulated towed aircraft system, as shown in Fig. 4.

The kinematics of the three-body articulated towed aircraft system can be developed by combining the single-body kinematics of each component. The tow bar, attached to the tow tractor's rear hitch, is the first passive vehicle in the three-body articulated towed aircraft system. As this research is concerned with only simulating the towed aircraft system, for simplification, it is assumed that the tow tractor's rear hitch is at the center of the rear axle. It is also desired to implement some physical constraints of the towed aircraft system. The tow bar can only rotate about the tow tractor's hitch so far before it collides with the tow tractor's structure. Similarly, the structure of the aircraft's nose wheel places a constraint on its maximum rotation angle. DIDO is capable of enforcing bounds on parameters, but it requires that they are represented as states. The heading of each element of the towed aircraft system should also be able to make as many complete revolutions, in either direction, as the path requires. Representing the headings simply as angles will force DIDO to unwind the headings if they are a full rotation from the goal. To enable this, the headings can be represented by two states containing

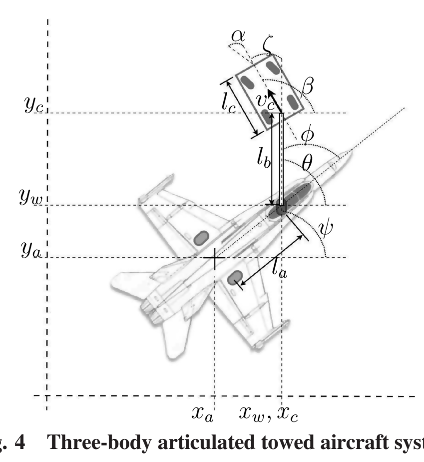


Fig. 4 Three-body articulated towed aircraft system.

the sine and cosine of the angle. The nonlinear kinematics are then given by

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{x} = \frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} x_c \\ y_c \\ \sin\beta \\ \cos\beta \\ x_w \\ y_w \\ \sin\theta \\ \cos\theta \\ \zeta \\ x_a \\ y_a \\ \sin\psi \\ \cos\psi \\ \phi \end{bmatrix} = \begin{bmatrix} v_c\cos\beta \\ v_c\sin\beta \\ \cos(\beta)\dot{\beta} \\ -\sin(\beta)\dot{\beta} \\ v_w\cos\theta \\ v_w\sin\theta \\ \cos(\theta)\dot{\theta} \\ -\sin(\theta)\dot{\theta} \\ \dot{\beta}-\dot{\theta} \\ v_a\cos\psi \\ v_a\sin\psi \\ \cos(\psi)\dot{\psi} \\ -\sin(\psi)\dot{\psi} \\ \dot{\theta}-\dot{\psi} \end{bmatrix}$$

$$= \begin{bmatrix} v_c\cos\beta \\ v_c\sin\beta \\ \cos(\beta)\frac{v_c\tan\alpha}{l_c} \\ -\sin(\beta)\frac{v_c\tan\alpha}{l_c} \\ v_c\cos\zeta\cos\theta \\ v_c\cos\zeta\sin\theta \\ \cos(\theta)\frac{v_c\sin\zeta}{l_b} \\ -\sin(\theta)\frac{v_c\sin\zeta}{l_b} \\ \dot{\beta}-\dot{\theta} \\ v_c\cos\zeta\cos\phi\cos\psi \\ v_c\cos\zeta\cos\phi\sin\psi \\ \cos(\psi)\frac{v_c\cos\zeta\sin\phi}{l_a} \\ -\sin(\psi)\frac{v_c\cos\zeta\sin\phi}{l_a} \\ \dot{\theta}-\dot{\psi} \end{bmatrix}, \quad \text{and} \quad \mathbf{u} = \begin{bmatrix} v_c \\ \alpha \end{bmatrix} \tag{2}$$

with the variables defined by Fig. 4.

These equations could enable a persistent monitoring system to propagate the motion of a towed aircraft, forward in time, based upon the measured locations and orientations of the vehicles involved. They can also be used with DIDO, providing the dynamics upon which to plan the optimal path to the desired position on the flight deck.

E. Aircraft Tow Procedures

Towing aircraft on the flight deck or hangar bay of an aircraft carrier is a carefully planned procedure, with standardized practices outlined by the CV Naval Air Training and Operating Procedures Standardization Instruction [31]. This instruction calls for the following minimum personnel when towing an aircraft: 1) director, 2) tractor driver, 3) plane captain, 4) two plane handlers, 5) two wing safeties (when required), and 6) tail safety (when required).

For a fixed-wing aircraft, such as an FA-18C Hornet, this means that nine personnel are required to move the aircraft. The director is responsible for the entire procedure. The plane captain provides braking control for the aircraft. The plane handlers insert the chocks whenever the aircraft is at rest.** The wing and tail safeties walk in a fixed position relative to the wing tip or tail to ensure that no collisions occur in that area [31].

The director is required to maintain visual contact with the plane captain at all times, and all personnel are equipped with whistles, which they must hold in their mouths, to signal each other [31].

**The plane handler and wing safety roles are typically fulfilled by the same personnel when ashore.

V. Testing Setup

This section describes the tests conducted at Naval Air Station (NAS) Oceana, designed to determine if position and velocity information provided by the Global Positioning System (GPS) are capable of supporting a system to monitor the position, orientation, and velocity of aircraft, equipment, and personnel on the flight deck of a USN aircraft carrier.

The purpose is to observe the movement of USN aircraft and sailors as they perform tasks similar to those performed on the flight deck of an aircraft carrier. By observing these tasks, a better understanding of the motion of aircraft, equipment, and personnel on the flight deck can be gained. These tests were conducted at a shore installation, but the differences in aircraft handling between sea and shore are minimal.

Six Leica GX1210 and three NovAtel OEMV dual-frequency GPS receivers were used to collect data. The default GX1210 is only capable of single-frequency ($L1$) measurements, but the six units provided by the Air Force Institute of Technology Advanced Navigation Technology Center have been upgraded to support dual-frequency ($L1$ and $L2$) measurements. Each device is capable of tracking 14 satellites simultaneously on each frequency. Measurements were taken at 5 Hz and recorded to a flash memory card. A carrier-phase solution, with differential corrections applied, was generated by NovAtel Waypoint GrafNav in postprocessing [32].

The tests recorded the position, orientation, and velocity of an aircraft as it was towed from one spot to another on the NAS Oceana flight line, as well as the position and velocity of the personnel required for the towing. This procedure is virtually identical to that performed onboard an aircraft carrier. A photograph of the test being conducted is presented in Fig. 5, depicting the antennas mounted on USN cranials and wing-tip-mounted GPS recorders.

The purpose of this test was to gather data that fully described the motion of an aircraft being towed and the personnel around it. An aircraft was towed to a designated location on the flight line and back during both day and evening shifts, providing different personnel to conduct the procedure.

At the conclusion of the evening aircraft tow, the personnel were directed to fold and unfold the wings. This allowed the mounted recorders to observe the motion of an aircraft's wing tips as they folded and unfolded. Folding the wings of an aircraft leads to a reduced footprint on the deck of an aircraft carrier, but if they unfold inadvertently, they can damage nearby aircraft. The goal of this test was to collect data on the folding and unfolding of wings, so that an algorithm could be developed to detect this motion.

VI. Results

This section describes the results of the tests conducted at NAS Oceana, Virginia. Topics include the measurement of aircraft wingspan b, the calculation of the position (x_a, y_a) and the heading ψ, and the path along which the aircraft was towed. Path-planning results based upon the measured data are also presented.

A. Aircraft Wingspan

The two Leica recorders mounted on the wing tips provided an excellent indicator of the accuracy and precision of the GPS solution. The recorders were strapped to the inboard side of the wing-tip missile pylons, using nylon pouches made by squadron personnel. The distance between these pylons is fixed when the wings are spread, so the only variation should result from the placement of the recorders along the length of the pylon. According to [4], the wingspan of an FA-18C Hornet is $b = 11.43$ m.

Figure 6 shows the wingspan measurements taken during the morning and evening tow procedures. Of note is the increased noise

Fig. 5 Photograph of aircraft being towed at NAS Oceana.

level in the latter phase of the evening test. In this portion, the wingspan measurement varies about the actual, but it does approach it. This error is likely due to GPS multipath error, where the antenna receives both the direct transmission from the satellite and a reflection from the body of the aircraft. The small difference in distance measurements from the actual wingspan is attributable to imprecision in the location of the phase center of the antennae.

B. Heading and Velocity

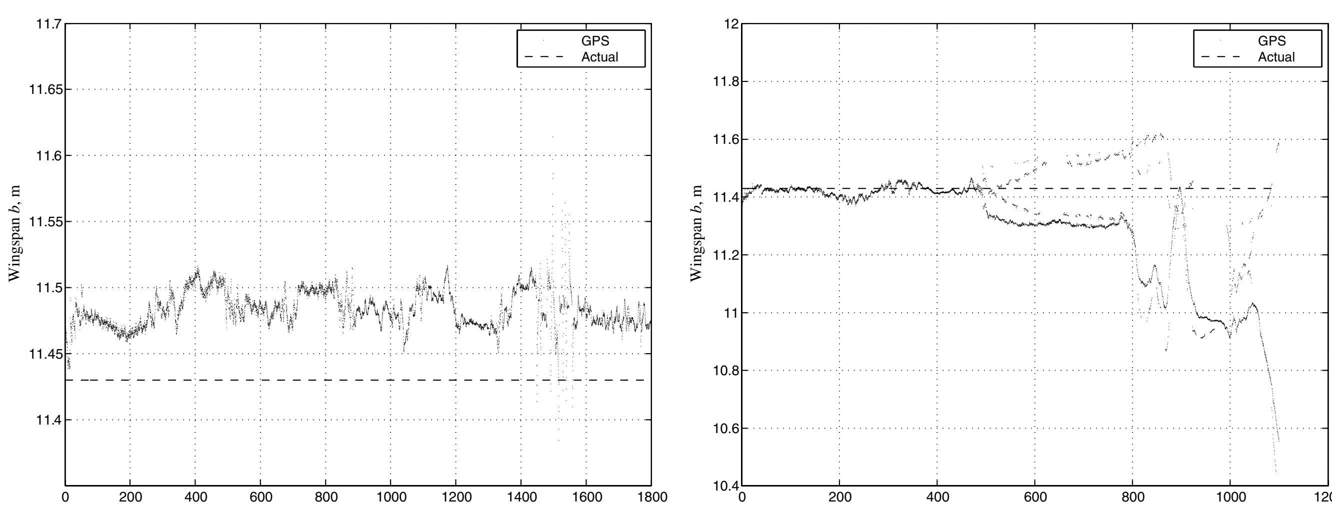
The heading of the aircraft ψ is calculated from the measured antenna locations, using the four-quadrant atan operator. To determine the heading rate, it was necessary to numerically differentiate the calculated heading data, a process which often introduces noise into measurements. A velocity profile was similarly calculated from the position measurements. One potentially useful element of information that can be derived from the observation of an aircraft tow procedure is the maximum turn rate and velocity used. This can be used to provide a motion planning algorithm with more realistic estimates of the vehicle capabilities. The maximum turn rate is a function of the nose wheel angle and the maximum tow cart velocity. While the maximum turn rate used in these tests ashore may not be the maximum capable, it should be on the same order of magnitude. The heading rate and velocity statistics of the tow procedure conducted at NAS Oceana are provided in Table 3.

C. Aircraft Tow Route

Analyzing the route taken with the towed aircraft allows for analysis of safe distances between aircraft (ashore) and route preferences. Figure 7 shows the path taken for both morning and evening tow procedures. It is clear from these data that there are set routes between the rows of aircraft parking spaces and that, during this test, two of them were used. The location of parked aircraft is an estimate based upon visual observations of the aircraft present.

D. Personnel Location

Figure 8 provides the relative location of the wing and tail safeties throughout all movement phases, both morning and evening. The data show the aggregate positions of five personnel, three as wing safeties and two as tail safeties. Using these data, it was straightforward to create bounding boxes, as shown. With further study, these bounding boxes could be treated as required positions for personnel towing an aircraft. Bounding boxes for the director and tractor driver could be created with more data on their positions during an aircraft tow procedure. If a sailor leaves the bounding box while the aircraft is in motion, the director could be alerted.



a) Morning **b) Evening**

Fig. 6 NAS Oceana aircraft wingspan measurements.

Table 3 NAS Oceana aircraft motion statistics

Time	$\dot{\psi}_{\max}$, deg/s	$\bar{\dot{\psi}}$, deg/s	$v_{a,\max}$, m/s	$\bar{v}_a$, m/s
Morning	8.1480	0.7015	0.5117	0.1338
Evening	8.5982	0.2999	0.5929	0.1146

E. Wing Fold

Following the conclusion of the evening tow procedure, the personnel involved manually folded the wings of the aircraft. The wingspan calculated from the recorder positions during this period are presented in Fig. 9. It is difficult, due to the noise in these data caused by GPS multipath errors, to pick out the exact moment when the wing-fold procedure started.

F. Path Planning

In order for a persistent monitoring system to provide early warnings of hazardous situations, it must be capable of predicting the path of objects on the flight deck. If DIDO is provided a cost function $J(\mathbf{x}, \mathbf{u}, t)$ that, when minimized, simulates the objectives of the personnel involved in the towing procedure, then DIDO should predict a path similar to the one taken. In the simulation, only forward motion of the aircraft was allowed for simplification; however, this constraint could easily be removed. The measured path, taken from the first portion of the evening phase, is shown in Fig. 10 and contains only forward motion.

The procedures for towing aircraft are designed to minimize the risk to aircraft and personnel. The decisions made by the personnel performing the tow procedure should also be to minimize risk. From the measured path shown in Fig. 10, it was observed that straight paths are desired over long curves. This is likely due to greater risk of collision with other aircraft or personnel during turns, as the motion of the aircraft (two articulated linkages behind the trailer) is sometimes difficult for the director and tractor driver to predict. It is also more challenging for the wing and tail safeties to walk in a curve rather than a straight line. So the tow tractor steering angle as a function of time $\alpha(t)$ should be minimized. A cost function that simulates this desire for straight paths is given by

$$J(\mathbf{x}, \mathbf{u}, t) = \int |\alpha(t)|\, \mathrm{d}t \tag{3}$$

Other parameters could be used in the cost function as well. Minimizing ζ and ϕ may provide even closer results. Using DIDO to find a path and minimizing this cost provides the path shown in Fig. 10. The scripts used for this problem were based on work by Hurni et al. [25,33,34]. The computation time for this path was over 30 min on a computer with a dual-core processor. While the paths do not match exactly, this system can be used to warn personnel of potential mishaps outside their field of view. This initial development of a path-planning algorithm was performed to guide future research in flight-deck monitoring. An algorithm that computes a path similar to that taken by an experienced towing crew could be used for path prediction of towed aircraft or path planning for UAVs.

VII. Summary

The subject of this research is the feasibility of a persistent monitoring system for the flight deck and hangar bay of an aircraft carrier. Such a system would continually monitor the position and orientation of all aircraft and SE, the position of all personnel on the flight deck, and the state of critical flight-deck systems, such as the up/down status of the JBDs. Such a system would provide this information in a format easily understandable by decision makers, so that they could improve the safety and overall efficiency of flight-deck operations. The system should also autonomously notify

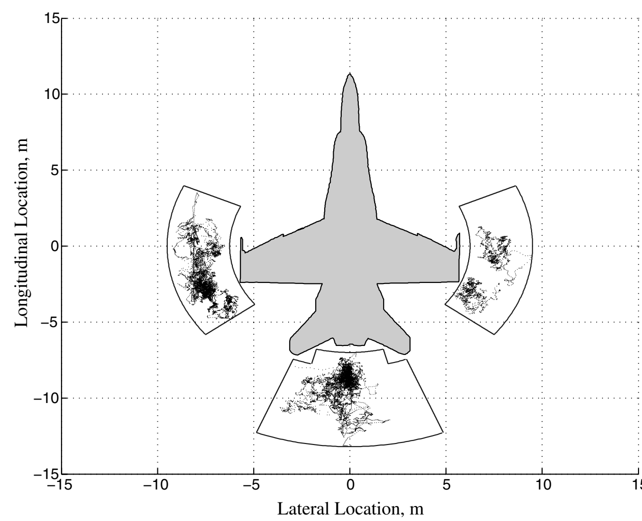
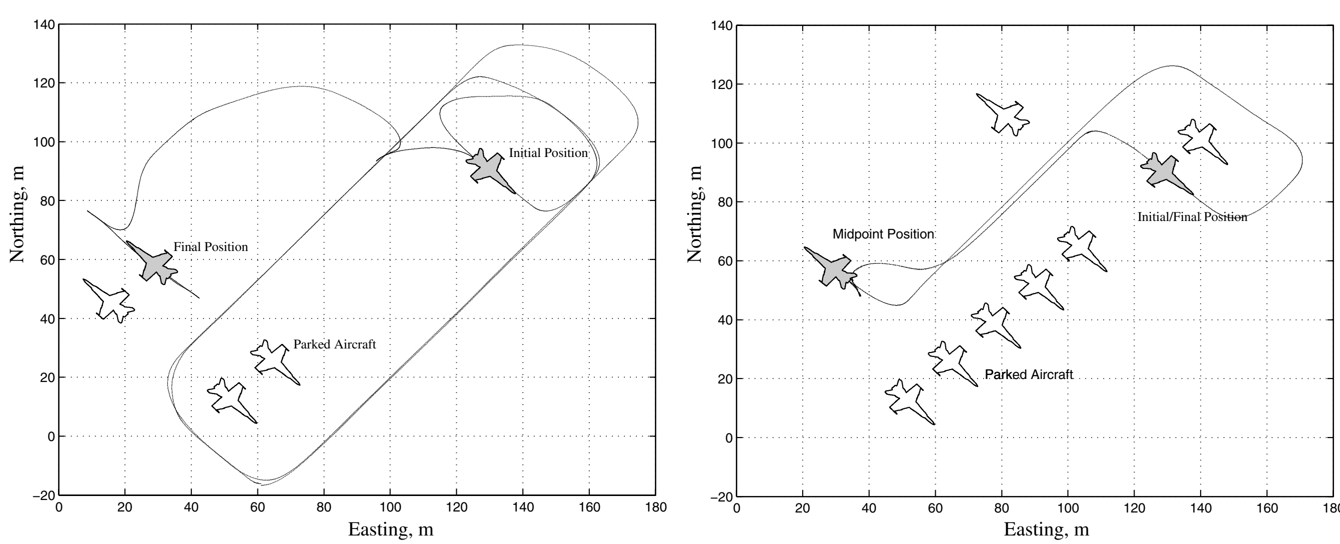


Fig. 8 Relative personnel position: wing and tail safeties.



a) Morning **b) Evening**

Fig. 7 NAS Oceana aircraft tow route: locations of parked aircraft are estimates.

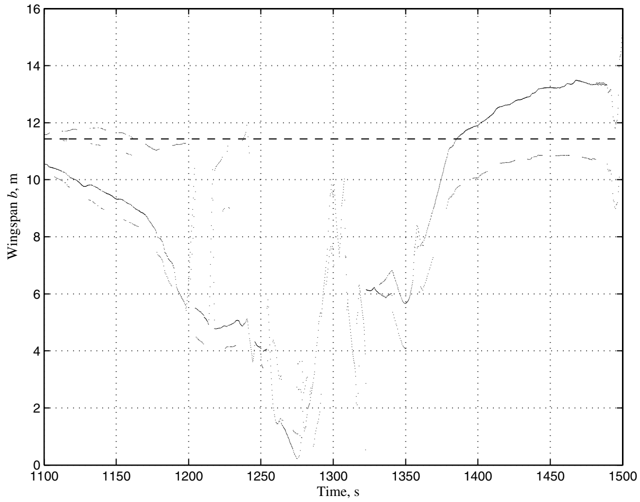


Fig. 9 Wing-fold wingspan measurements.

personnel if they are approaching a hazardous area or situation. The goal of such a system is a more efficient flight deck that can 1) reduce the occurrence of flight-deck mishaps, and 2) provide accurate recordings of flight-deck operations for analysis.

From the results of this research, some overall conclusions can be made about the feasibility of a persistent monitoring system.

1) Because of a number of factors, such as the high multipath error observed, the high cost of dual-frequency GPS receivers, and the risks involved in relying on satellite transmissions, the measurement system should not exclusively rely on GPS for the highly accurate measurements required.

2) Substantial computing power is required to predict the path of a towed aircraft and process state information from potentially hundreds of positioning devices. The ability to closely match the actual path could significantly improve the system's ability to recognize potential mishaps.

This section will explore how modern GNC concepts can be applied to potentially prevent mishaps on the flight deck. The examples used are taken from the mishaps of Table 2.

A. Spotting Mishaps

An extremely common spotting mishap is a parked aircraft being struck by a JBD or barricade stanchion. Figure 11 illustrates an aircraft parked in such a way that the raising of a barricade stanchion will impact the aircraft. A level one system, one which measures aircraft position and orientation, could potentially prevent such a mishap if the measurements are sufficiently accurate.

A distance measurement between the aircraft and the barricade stanchion could be used to recognize a potential mishap. If the distance between an aircraft's center and the barricade stanchion is below a certain threshold, then a nearest-neighbor search should be conducted to determine if any point on the aircraft is near zero distance, in the two-dimensional sense, from any point on the stanchion. If this is true, then a persistent monitoring system could be set to handle the situation in different ways.

Having determined there is potential for a spotting mishap, the system could warn the taxi or tow director that the aircraft is parked in an undesirable location. Alternately, the system could warn flight-deck control that the aircraft was parked in a hazardous location, leaving it to the handling officer to determine whether it should be moved. If the decision is made to park the aircraft in a potentially hazardous location, for whatever reason, then the system could alert flight-deck control of this hazard again if the barricade stanchions are set to be raised.

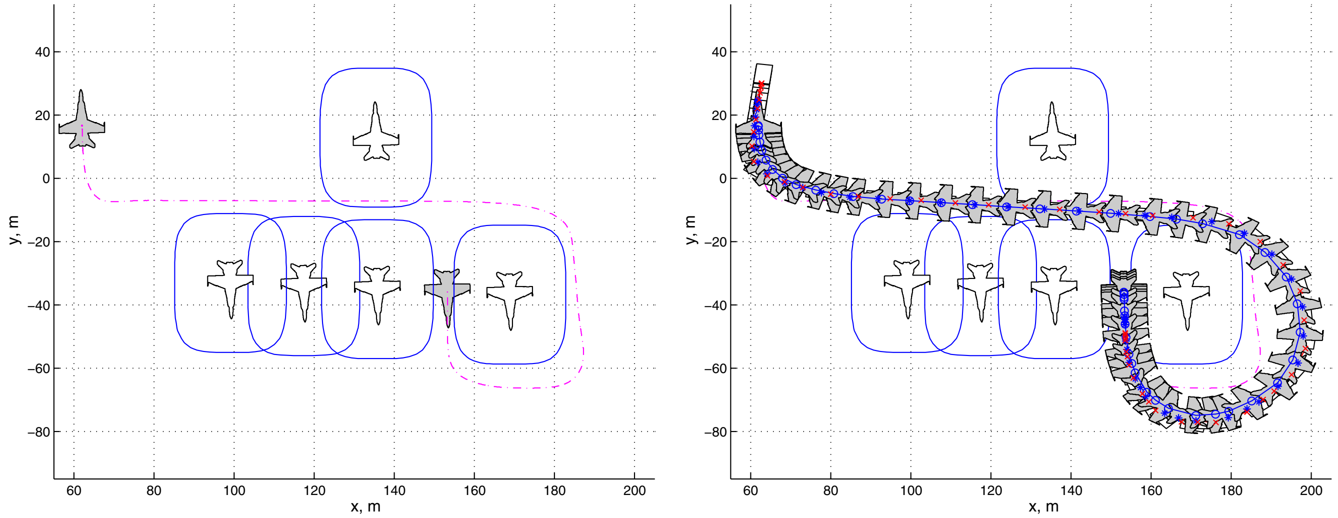
Considering the prevention of a spotting mishap also allows an analysis of the level of accuracy required for both position and orientation measurements. Figure 11 shows the effect of just 5° of heading angle measurement error. With this error, a monitoring system could not determine whether the stanchion would collide with the aircraft.

The results of the heading calculations from the data collected at NAS Oceana demonstrate the ability of precision GPS to provide accurate and low-noise headings. Any radio navigation system with centimeter-level accuracy should be able to provide similar results.

B. Towing Mishaps

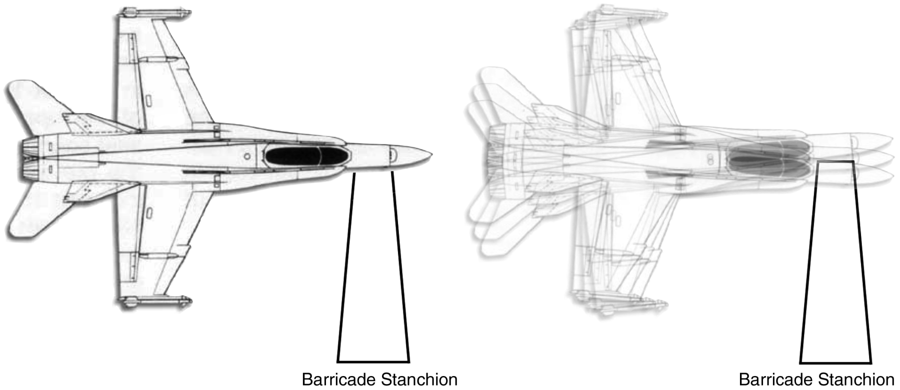
Potential towing mishaps, such as a collision with a parked aircraft in the hangar bay, could be recognized by a level one system. A path-planning system, such as one that uses DIDO, could continuously compute a reasonably close prediction of the path of the towed aircraft system. If a level two system is implemented, it could monitor both aircraft and SE.

Many towing mishaps involve a towed aircraft being parked in close proximity to a stationary aircraft. In this case, the persistent monitoring system could continuously calculate the nearest-neighbor distance to surrounding aircraft, equipment, and personnel. If this distance is less than a predetermined threshold, the system could alert all personnel involved to the risk of collision.



a) Path planning: measured path **b) Path planning: predicted path**

Fig. 10 Path-planning results.



a) Precise measurement: the barricade stanchion will impact the aircraft when raised

b) Imprecise measurement: it is unknown if the barricade stanchion will impact the aircraft when raised

Fig. 11 Recognizing spotting mishaps.

C. Taxiing Mishaps

A level one system, measuring the position and orientation of all aircraft on the flight deck, should be able to recognize a potential taxiing mishap. Typically, this type of mishap involves a collision between two aircraft. While it could be possible to warn of such a potential mishap simply by calculating the distance between the aircraft and their relative velocity, the use of a path-planning system, such as one that uses DIDO, could significantly increase the time that personnel would be given to react to the warning and reduce the occurrence of false warnings.

If a potential mishap is detected, the pilot of one aircraft could be directed to stop, while the other moves beyond the collision event horizon. In the case of a path becoming obstructed, the taxi director and pilot could be provided with a new path to follow.

D. Exhaust Mishaps

With the heading rate calculations and personnel position measurements, it is possible for a level three system to recognize a potential exhaust mishap involving a sailor. In a typical scenario, the system could watch for a taxiing aircraft performing a turn on deck, with a sailor standing still in a location the exhaust will pass through. Such a scenario is depicted in Fig. 12.

To prevent injury or damage resulting from this type of mishap, the system could use not only the position and orientation measurements, but a desired location as determined by flight-deck control. A taxiing aircraft is generally heading toward a catapult, a dearming location, or a parking spot, and the desired locations are set by flight-deck control. Starting from the aircraft's measured position and orientation, a path-planning system, such as DIDO, should provide a reasonable estimate of the path if a desired final position and orientation are known. The heading rate calculations can be used to determine the speed with which the exhaust hazard is approaching the sailor. With this information, it would be possible to determine the amount of time before the aircraft's exhaust poses a hazard to the sailor. The sailor could be alerted to this hazard with time to move out of the way or duck to avoid the exhaust. In a level four system, where the status of aircraft systems is reported to the persistent monitoring system via a data link, the actual throttle status could be used to determine the dimensions of the exhaust hazard area.

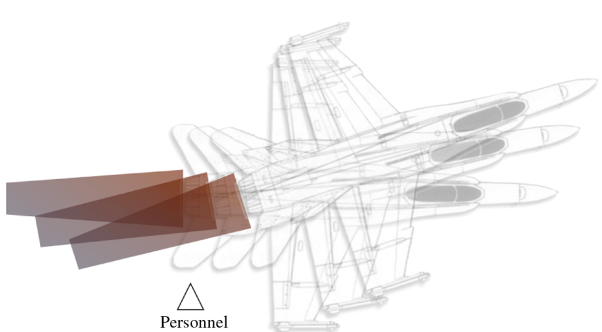


Fig. 12 Recognizing exhaust mishaps.

The ability of a persistent monitoring system to predict this kind of mishap would depend greatly upon the position measurement accuracy and precision. If position measurements are noisy, the heading rate calculations would be useless. Additionally, the rapid pace of events on the flight deck could require the system to have a particular measurement update rate to be fully effective.

E. Contact Mishaps

The contact mishap presented in Table 2 describes a Plane Handler, identified by the color jersey worn, being run over by the main mount of an aircraft. If a Level Three persistent monitoring system is implemented, it could issue warnings of such a situation. One potential prevention method is to use the personnel bounding boxes shown in Fig. 8. These bounding boxes are areas surrounding the aircraft where the personnel involved are expected to remain throughout the procedure. The system could inform the Director, Tractor Driver, and Plane Captain when all personnel are positioned within the bounding boxes, and only then would they start moving the aircraft. If the pilot is operating the aircraft, then the pilot could be given permission to move once all personnel are positioned within their respective bounding boxes.

Preventing this type of mishap imposes requirements on the accuracy of both aircraft and personnel position measurements. As personnel often travel underneath the wing or fuselage of an aircraft during flight-deck operations, it also presents requirements for signal reacquisition time for radio measurements or drift rate for inertial measurements.

F. Engine Mishaps

With a level three system monitoring the movements of personnel, the distance between a person and a propeller could be measured and a warning issued if the distance is below a certain threshold. It would also be possible to create a hazard zone directly in front of the propeller. If a person enters the zone, then the system would alert them to leave it immediately. Figure 13 illustrates notional hazard zones around the propellers of an E-2C Hawkeye.

The propeller hazard zones only exist when the propellers are turning. Maintenance must be performed on the propellers, so the persistent monitoring system must somehow be aware of this status. An aircraft scheduled for a flight within a specified time, for instance, could automatically be checked for engine hazard violations. Alternately, a supervisor on the flight deck could be required to inform flight-deck control to disable the engine hazard violation warnings for maintenance purposes. If a level four system is in place, then the engine status reported by the aircraft could be used to determine hazard zone status.

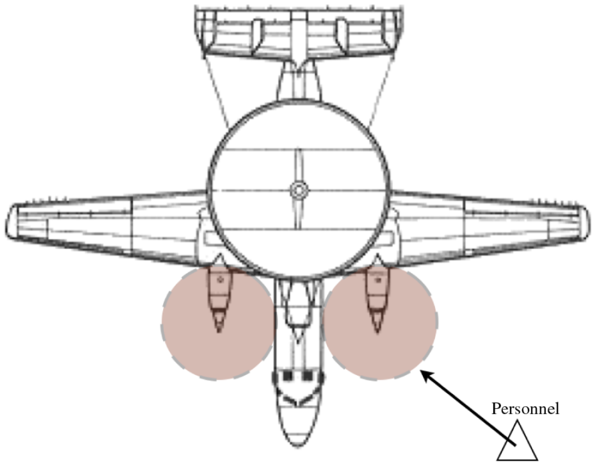


Fig. 13 Recognizing engine mishaps: the hazard zones are representative of propeller hazard areas, not comprehensive for the depicted aircraft.

G. Wing-Fold Mishaps

One method to potentially prevent wing-fold mishaps is a level four system, where the aircraft have been modified to report their wing-fold switch status to the persistent monitoring system. If the measured position and orientation of the aircraft would force its unfolding wings to impact another object, then the system would not allow the wings to unfold. This modification could be prohibitively expensive, but future aircraft could have it included earlier in the acquisition process at a reduced cost.

Another method to detect a potential wing-fold mishap is to measure the distance between wing-tip mounted receivers as part of a level one system. The rate at which the wings were folded at NAS Oceana was slow, because the fold was performed manually. When an FA-18C is powered, the wing-fold process is significantly faster. The magnitude of the wingspan measurement slope in Fig. 9 would be greater for a powered wing fold and therefore easier to detect.

A persistent monitoring system's performance specifications, such as accuracy and update rate, will greatly affect its ability to recognize this type of mishap. Using wing-tip mounted receivers to detect the wing-fold motion may also impose constraints on the physical design of the receiver. Significant multipath error was observed when the wings were folded and the antennae were pointed toward the aircraft.

H. Nonaviation Mishaps

A nonaviation mishap, such as an aircraft being struck by a forklift during an underway replenishment, is very similar to a towing mishap. The same processes to recognize a potential mishap, path prediction and distance calculation, should be applicable.

The challenge inherent to nonaviation mishaps is that they do not exclusively involve aviation assets or personnel. The forklifts and pallet jacks used by the supply department would need to be monitored, and the personnel operating them would have to be trained to respond to hazard warnings. Attempting to prevent this type of mishap leads to considerations on the pervasiveness and simplicity of a persistent monitoring system, as nonaviation personnel would only occasionally be required to use it.

VIII. Conclusions

This research set out to determine the feasibility of using a persistent monitoring system to potentially prevent mishaps onboard a USN aircraft carrier. From the data collected, it is clear that radio navigation can provide the accuracy to collect the information necessary to recognize a hazardous situation. Actually implementing a system to provide this functionality is a complex and challenging task. Arguments have been provided that significant cost savings could be achieved by implementing such a system. It is up to USN leadership to determine if the operational and safety benefits outweigh the costs.

Acknowledgments

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