AUTONOMOUS VEHICLES FOR FLIGHT LINE USE

Graduate Research Paper

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AFIT-ENS-MS-21-J-065

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT-ENS-MS-21-J-065

AUTONOMOUS VEHICLES FOR FLIGHT LINE USE

Graduate Research Paper

Presented to the Faculty

Department of Operational Sciences

Graduate School of Engineering and Management

Air Force Institute Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Operations Management

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June 2021

AFIT-ENS-MS-21-J-065

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Abstract

The purpose of this proof-of-concept study is to discover if autonomous vehicles (AV) can work on and within the United States Air Force (USAF) flight line infrastructure to free flight line personnel for value-added roles. An autonomous vehicle was deployed to Joint Base McGuire-Dix-Lakehurst (JB-MDL), NJ, to document the limitations and uses and sought to answer; can an autonomous vehicle work on the flight line? The study revealed that an AV could operate on the flight line safely, in a valuable and effective manner, and provide some labor-hour cost-savings benefits when applied in foreign object and debris (FOD) collection tasks. The study results were an extensive development of the problem set required to fully employ autonomous vehicles in flight line or aerial port environments. A 'lighthouse' testbed should be established at JB-MDL because of the cross-service environment and access to the Air Mobility Command's (AMC) Expeditionary Center (EC).

To my family for their support and patience and the dedicated men and women of the maintenance community.

Acknowledgments

My first thanks are to my family, who supported this project and encouraged me to continue pursuing autonomous technology on the flight line despite the many hurdles faced. Second, I would like to thank the JB-MDL leadership, maintenance, and innovation team who helped coordinate and execute the study. Without them, this would not have been possible. Specifically, the initial autonomous vehicle "cadre," MSgt Austin Barkdoll of the 305 MXG, SSgt Andrew McClain of the 305 APS, SSgt Mitchell Scott of the 305 MXS, SrA Jeremiah Bethea of the 305 AMXS, and SrA Jay Miller of the 605 AMXS deserve tremendous thanks and appreciation. Additionally, I would like to thank my faculty advisor Col(s) Jason Anderson, for his undying enthusiasm and constant pursuit to improve his students' development. I would also like to thank Brig Gen Linda Hurry and the HAF/A4L team for sponsoring this research. Finally, I would like to thank the generous team at Maren-go, not just for their support of the study but for their passion for seeking solutions to improve the lives of the men and women of our military as we ventured into new territory applying autonomous vehicles on the flight line.

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AUTONOMOUS VEHICLES FOR FLIGHT LINE USE

I. Introduction

Emerging technologies are advancing rapidly, and the birth of Autonomous Vehicles (AV) and Autonomous Material Handling Robots (AMR) and their applications have numerous implications. Autonomous technology has become cheaper and more accessible, leading to broader uses (Bagloee et al., 2016). While there is wide use of AVs in ground transportation, using AVs and AMRs to transport materials and supplies on the aircraft flight lines is a relatively new concept to be explored (Hancock et al., 2019; Ma et al., 2020; Meldert et al., 2016).

As AV technology adapts to new environments, the implications for aircraft and flight line maintenance use could present a competitive edge going forward. This paper briefly outlines maintenance workflow, then reviews the literature on the safe and effective use of AVs and their add-on software. Lastly, this paper assesses the AV's ability to operate in a flight line environment and provides a conclusion and recommendation to the reader.

Background and Problem Statement

Aircraft maintenance organizations seek to produce mission-capable aircraft for effective sorties, whether for combat, proficiency, or training. As process owners, logistics and aircraft leaders constantly seek efficiency and effectiveness of operations. To execute its mission, maintenance organizations must have appropriately trained, equipped, and resourced technicians. Tragically, over the last eight years the Air Force has continued to lose experienced maintainers with no goal or strategy to retain them years (Losey, 2019) Additionally, from 2013 to 2018 the Air Force experienced 198 deaths, 157 aircraft destroyed, and 9.41 billion dollars lost attributed to the degraded morale caused by "a lack of flight hours, a stressed supply chain, high operational tempo, and administrative distraction" (Myers, 2020). The future of aircraft maintenance requires solutions and processes that maximize the USAF aircraft maintainers' capabilities and alleviates redundant, non-value-added tasks from maintenance operations. Augmenting flight line-support technicians' workload would free them for value-added roles that bolster aircraft generation and solving complex problems (Seegrid, 2018). A suggested solution to augment maintainers' workload is using autonomous vehicles to fill non-value-added roles, but a lack of research and application has occurred in this arena (Meldert et al., 2016).

Research Objectives/ Questions/Focus

The purpose of this proof-of-concept study is to discover if autonomous vehicles can work on and within the United States Air Force flight line infrastructure. An AV will be deployed at Joint Base McGuire-Dix-Lakehurst, NJ, to document its capabilities and limitations. Questions to be addressed in this research include:

- Can an autonomous vehicle work on the flight line?
    - Investigative questions:
        1. Are autonomous vehicle operations on the flight line safe?
        2. What are the uses of autonomous vehicles on the flight line?
        3. Are autonomous vehicles on the flight line effective?
        4. Does add-on software eliminate bottlenecks, or does it increase them?

This paper will assess the performance of autonomous vehicles assisting in material handling roles and discovering additional functions in real-world conditions by employing an exploratory research method and applying Strategic Capability analysis. This research will focus on the ability of an AV to safely and effectively operate on the flight line. The researcher observed the vehicle performance and conducted an assessment of capability analysis with recommendations.

Methodology

This research has utilized the exploratory research design method and adapted the strategic capabilities assessment framework of an autonomous vehicle's performance to fit into flight line operations. This research will observe and assess the application of AVs on flight line operations and their potential to further other use cases. Whether or not a capability is considered strategic is its ability to mutate and adapt to other capabilities (Johannesson & Palona, 2010).

Assumptions/Limitations

Limitations to research include the autonomous vehicle hardware and software performance, local Air Force base limitations and restrictions, and potential weather that may impact operations. Limited experience with the technology and learning curves reduces the full exploitation of the technology as well. The demonstration was limited to 10 days with a team of users whose expertise is focused on aircraft maintenance and who are unfamiliar with AV technology. The area of operations on a flight line was limited to maximize safety and avoid active flying operations. Results may differ at other bases due to variance in policy, airfield layout, and local weather conditions. The demonstration was conducted at Joint Base McGuire-Dix-Lakehurst in April-May of 2021.

Implications/Summary

A practical demonstration of AV capabilities on the flight line can further define the constraints to employing AVs. This study can also encourage future uses of AVs for all material handling needs, inspection, personnel transport, fuel, and ammunition delivery. There are also implications for loading, maintenance, diagnostics, and troubleshooting technologies to augment our workforce while shaping future policy and synchronizing the flight line of the future.

II. Literature Review

Overview

The literature review addresses maintenance workflow and the safe and effective use of AVs. Additionally, this review addresses the consequences of added software required to operate autonomous vehicles.

Current Flight line Operations

Current flight line organizations have evolved since the first flying squadrons in 1917 as aircraft have become more complex (George et al., 2003). As aircraft grow in complexity, the alignment and specialization of aircraft maintainers have increased, but the overall repair and support request processes of the flight line have changed very little (Habib & Turkoglu, 2020). As aircraft maintenance becomes more specialized and technical, this phenomenon fractures maintenance velocity by requiring differing training, technical orders, test equipment, and processes for parts and equipment.

If a piece of equipment or part is needed while the Airman is working on an aircraft, they must work through supply to call or text the flight line expediter, who will retrieve the required equipment and drive it to the maintenance location. These requests often leave the maintainer to wait on the expediter. If the wait is too great, the maintainer will walk to the equipment area to retrieve the equipment. These delays are slowdowns and add frustration to the maintenance technicians during their duty day (Campos et al., 2012). Figure 1 illustrates the numerous steps that could be affected by automation for the C-17 aircraft. For example, of the 20 possible actions, 14 (70 percent) could be affected by automation. Figure 2 illustrates the KC-10 aircraft maintenance, and of the 26 possible steps, 21 (81.7 percent) could be affected by automation. A simulation conducted on flight line AVs increased the value-added time for the expediter by 7.2

hours for KC-10s and 1.9 hours for C-17 due to the AV's ability to carry equipment (Stanton, 2020). Maintenance and support personnel can utilize this return of value-added time for more complex problem-solving tasks (Seegrid, 2018). This portion of the literature review's primary focus is to familiarize the reader with current military flight line maintenance operations.

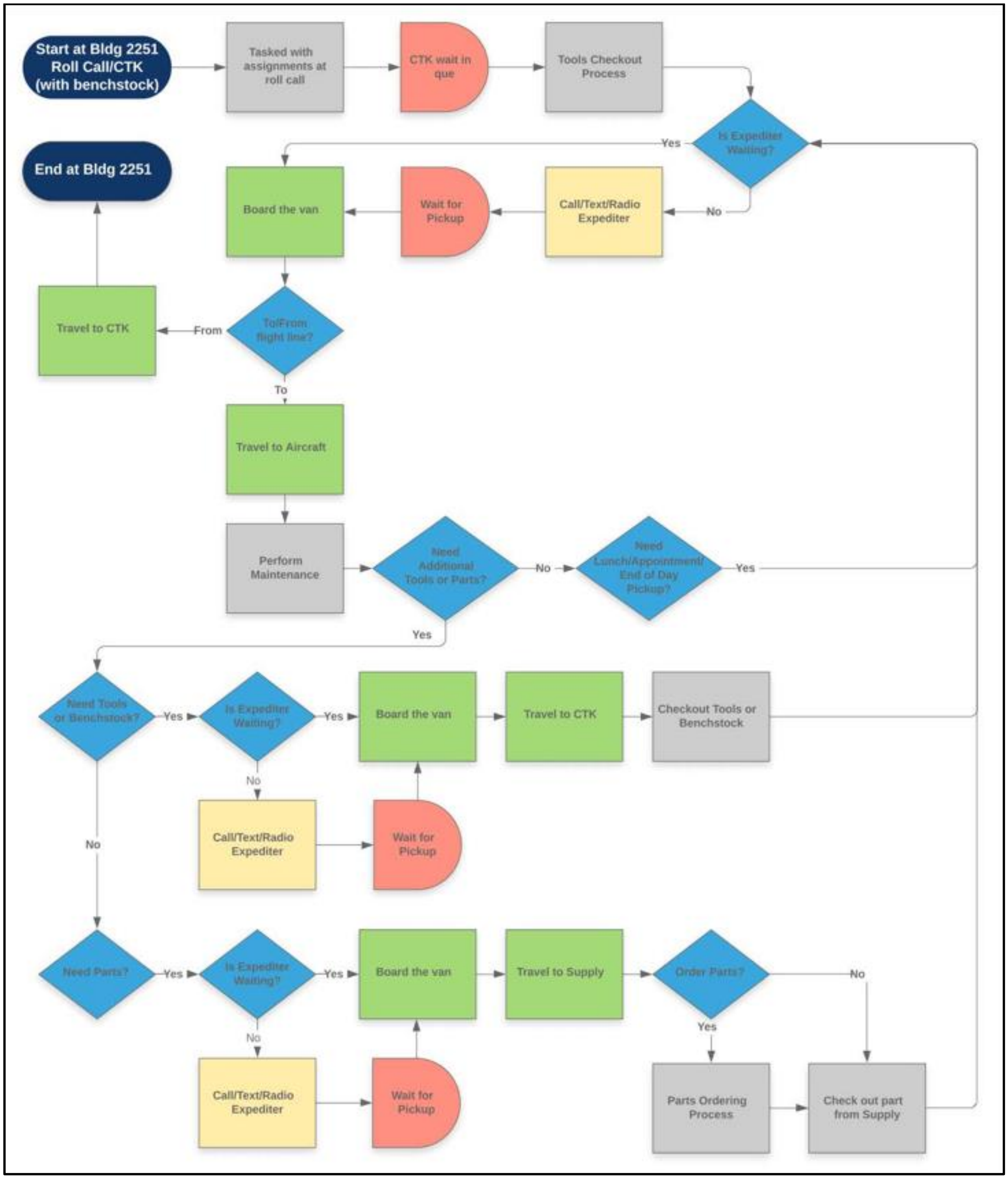

Figure 1. JB-MDL C-17 Maintainer Workday (Stanton, 2020)

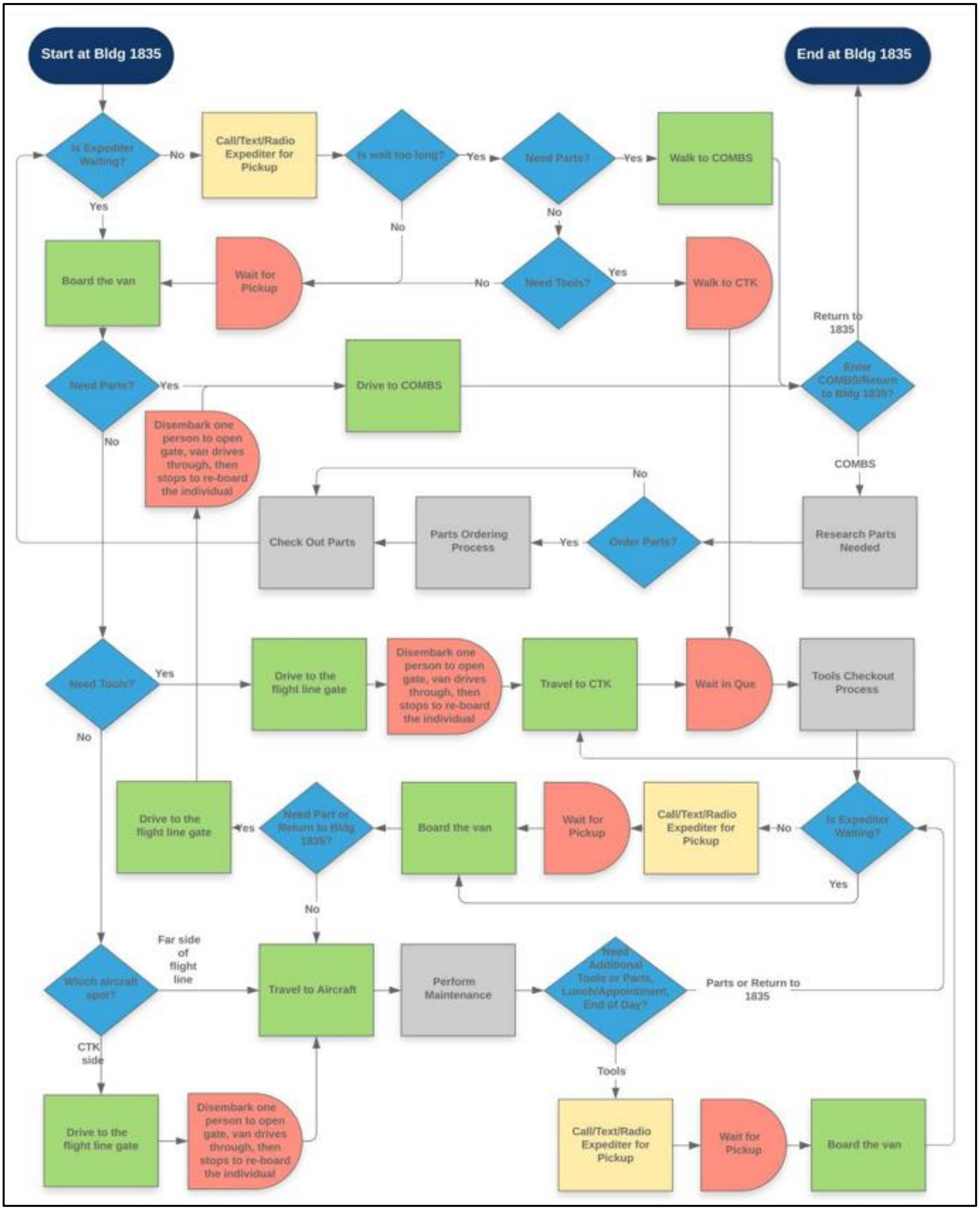

Figure 2. JB-MDL KC-10 Maintainer Workday (Stanton, 2020)

Autonomous Vehicles

Advances in autonomous vehicles have reached incredible capabilities compared to only a few years ago. As new sensors, software, and technologies are developed and improve upon, the velocity of a rapidly growing technology will increase (Rosique et al., 2019). This literature review will cover the safety of autonomous vehicles, their uses, effectiveness, and add-on software.

Safety

Because of the high error-prone activities of maintenance operations, process owners must continuously seek safe operations (Langer & Braithwaite, 2016). Additionally, studies show between 90-94% of road accidents are caused by human error and which at least, in part, has led to live tests globally to invest in autonomous transportation (Ruddy, 2017; Yurtsever et al., 2020). As the liability shifts from drivers to manufacturers, the AV market expects to increase overall safety (Marchant et al., 2012; Wan & Wu, 2018). For an autonomous vehicle to be considered safe, it must meet rigorous rules with billions of complex calculations every second. The definition of the word safe within the context of AVs is "Correctly implementing vehicle-level barriers such as obeying traffic laws (which can vary depending upon location) and dealing with non-routine road hazards…" (Koopman & Wagner, 2017). In addition to flight line driving regulations, this definition of safe operations was applied to the demonstration of the AV at JB-MDL. Figure 3 highlights the complexity and overlapping efforts to achieve safe operations for AV and AMR technology. Broadening the definition to include AMRs, to be safe, they must possess inherently safe operating systems, established fail-safes, tested safety margins, and procedural safeguards (Mohseni et al., 2020). Because of the potential risk of autonomous operations, policymakers must avoid disrupting any of these standards.

To illustrate this point, the researcher conducted an in-depth deliberate risk assessment with Air Force organizations to gain operating approval of an AV on the flight line. Further complicating this effort is integrating automation in "legacy" infrastructure that is not conducive to automated operations. Hangars, construction, moving aircraft, and natural hazards all pose potential safety concerns. For example, safety implications arise when AVs operate among human-driven vehicles (Straub & Schaefer, 2019) on roadways and in warehouses designed before AV technology was available (Gagliardi et al., 2012). Operations on military flight lines also include a complex network of communication channels required to safely operated aircraft.

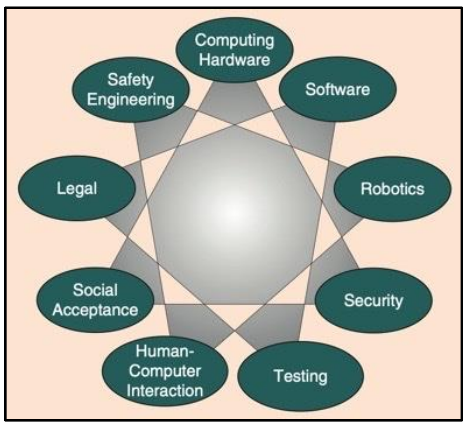

Figure 3. Inter-Disciplinary Safety Approach (Koopman & Wagner, 2017)

Although the safety implication of AVs appears promising, the Insurance Institute for Highway suggests that AVs will only be able to avoid one-third of vehicle accidents, which are attributed to misperceptions (Young, 2020). It is anticipated that AV and AMRs will significantly reduce accidents and congestion (Bagloee et al., 2016; Fragapane et al., 2021; Meldert et al., 2016; Wan & Wu, 2018), but vehicle accidents will continue to occur due to vehicle failure and unavoidable situations. It is expected that overall vehicle accidents will decrease, but new types of accidents will likely increase (Marchant et al., 2012) until firms design and implement safe and effective autonomous technology (Bartl, 2015; Bylsma et al., 2020).

Uses of AV

Today's uses of autonomous vehicles include improving efficiency and productivity in a variety of operations (C. Brown, 2012). The inherent benefits of AVs and AMRs make them useful in task-based activities with high repetition and low variability (Bayat et al., 2017; Gružauskas et al., 2018; Ma et al., 2020) such as traveling along a pre-set pathway conducting redundant tasks. AVs and AMRs are currently used in hospitals, warehouses, manufacturing, and several other environments (Fragapane et al., 2021). These tasks include moving equipment within a determined limit along a predetermined path with low variabilities. Uses are generally more acceptable when accuracy is preferred over urgency (Alessandrini et al., 2015). Flight line operations are relatively stable and follow a narrow set of operating procedures, making a possible environment for AVs to operate. Additionally, AVs have been helpful in areas where human lives are in danger, such as mining, explosive ordinance disposal, and dangerous search missions (C. Brown, 2012; Tucker, 2019). AVs are fully employed in low-population environments that are labor-intensive, such as earthmoving and agriculture (Ha et al., 2018) allowing humans to conduct other activities.

AV performance is poor when there is significant variability of data or uncertainty (Ma et al., 2020). The variability of weather conditions in outdoor environments or field conditions may lead to poor performance (Bayat et al., 2017). AVs yield poor results when standard sodium-vapor streetlights or LED lighting is used during hours of darkness, which results in washed-out image detection and inadequate responses (Maddern et al., 2014). Washed out imaging presents a concern because of the variability of lighting on flight lines at night. AV sensing equipment effectiveness is limited in poor weather conditions such as rain and snow (Ma et al., 2020).

The use of AVs should be avoided in situations that present numerous ethical, legal, political concerns that have yet to be experienced (Hancock et al., 2019; Marchant et al., 2016), such as the case with ethical programming decision making in AVs or the military application of some lethal AVs. Fundamental ethical questions arise with lethal military applications such as; "Will autonomous robots be able to follow established guidelines of the Laws of War and Rules of Engagement, and specified in the Geneva Conventions? Will robots know the difference between military and civilian personnel?" (Lin et al., 2008) Even though weaponized autonomous technology is extreme, some critics fear autonomy in any military operation can lead to unclear lines of responsibility when malfunctions and errors occur (Noorman & Johnson, 2014). This contrast of the human versus machine struggle highlights when autonomous and artificial intelligence capability outpaces human reasoning (Hancock et al., 2019). Today's ethical concerns are centered around weaponized autonomy and the eventual interaction between human negotiation in autonomous systems (Pagallo et al., 2018). This study will utilize AVs to augment human activities and is well within the acceptable use of the technology.

What is an effective AV?

An effective AV meets the users' needs and is cost-effective, sustainable, and adaptable (Gružauskas et al., 2018). Effective AVs and AMRs should result in some measured increase of efficiencies or productiveness and will decrease transportation costs and increase accessibility in some areas (Bagloee et al., 2016). AVs are effective when they meet the needs of their users and operate in predictable, specific environments with low variability (Ma et al., 2020) More specifically, AVs are most effective when working together through a connected network

(Yurtsever et al., 2020). Multiple AV and AMRs allow the prioritization of tasks and the AVs to communicate distances, locations, and tasks to create the most effective use of their power and energy resources (Mclurkin et al., 2006).

Air Force Technology adoption

If AV technology can demonstrate such added benefits, do we anticipate that the Air Force will quickly adopt the technology? Historically, no, but this does not come without reason. We have seen that early adoption of technology within the DoD frequently fails and is reduced to a "valley of death" (Coughlan et al., 2008) because of burdensome acquisition processes and lack of planning.

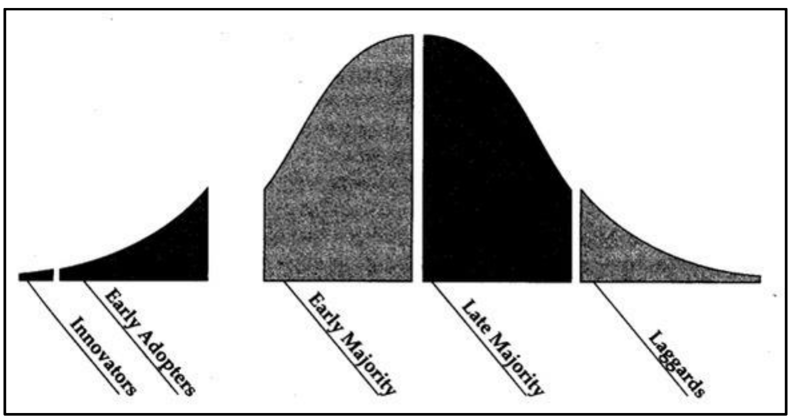

Figure 4. The Revised Technology Adoption Life Cycle (Linowes et al., 1999)

Three primary factors contribute to the lack of technology adoption: the requirements process, the planning and budgeting process, and the defense acquisition system (Coughlan et al., 2008). These decision-making tools are administrative burdens that involve thousands of members and years to navigate. To promote technology adoption, we must align “the incentive for all stakeholders and to specifically engage the end-user so that they 'pull' the new technology over the chasm" (Coughlan et al., 2008). Current policymaking, regulations, infrastructure, and financial investments make the adoption of technology a complex challenge facing organizations (Ruddy, 2017).

Companion Software Suites

Integrating software suites into the daily lives of employees brings promised capabilities and burdens. Mobile information platforms have been able to help some users overcome physical demands in traditional work environments (Yin et al., 2018). Specific to AVs, integrating mobile technology allows for control and dispatch of multiple vehicles and addresses priority command and control decisions (C. Brown, 2012). A centralized user interface enables the user to select one AV or the entire fleet to control and assess the environment (Mclurkin et al., 2006). The bottom line is that some form of add-on interface will be required to manage the AVs and is expected to provide some benefit but come at some learning investment cost to the user. Problems occur when software burdens the user with overload and does not provide the added benefit. One Air Force career utilizes more than 70 programs to conduct their day-to-day business (Biermann, 2019). Adding additional software to an employee's requirements can have stressful and counterproductive results (Yin et al., 2018) Add-on software can also bring additional training burdens and increase propriety software. In the Air Force specifically, because of lack of integration, many systems do not talk. In a 2018 survey, 70 percent of workers reported communication volume as a challenge, and 68 percent of employees had to navigate between multiple applications ten times per hour (Yin et al., 2018). Adding additional software that is not adequately integrated into Air Force member's current systems will potentially overload them.

In addition to employee overload, autonomy operations require large amounts of data and additional network connectivity (Klamt et al., 2020). Reducing required bandwidth is critical because network connectivity at many Air Force bases is limited. It is optimal when using fully integrated software that minimizes complicatedness, optimizes complexity, and maximizes control (Frese, 1987). To access the autonomous technology and fully exploit its capabilities, the user will need to access user-friendly interfaces to synchronize, dispatch, monitor, track, recall, and prioritize AVs and AMRs.

Summary

The review of the existing literature provided a contextual understanding of flight line operations, addressed the safety, uses, and effects of AVs. The review also discussed the pros and cons of adding add-on software needed by the user. The next chapter will address the methodology used to manage the research question.

III. Methodology

Overview

This research employed an exploratory research design method of emerging technology that allows for discovering new applications as the investigation progresses. The AV was then analyzed through a modified strategic capability framework for flight line use. This methodology also included reviewing operational flight lines and safety documentation. Observing the AV in flight line operations and interactions between the AV and maintainers provides valuable feedback in answering the investigative and research questions.

The research focus is to explore the infusion of autonomous vehicles on maintenance operations. To answer the investigative and research questions, the researcher set up an autonomous vehicle demonstration that assesses the ability of the AV to be effectively used on the flight line in various roles. The researcher will obverse the use-case data from the demonstration to answer the investigative questions and provide a strategic capability assessment.

Subjects

The subjects selected for this research were volunteers from the 305th Maintenance Group and Base Innovation team at Joint Base McGuire-Dix-Lakehurst, New Jersey. The researcher briefed the participants to conduct normal duties while utilizing the autonomous vehicle for equipment deliveries traditionally accomplished by the flight line expediter. The subjects work at the 605th Aircraft Maintenance Squadron, which performs maintenance duties on the KC-10 aircraft, the 305th Aircraft Maintenance Squadron, which performs duties on the C-17s 305th Maintenance Squadron who perform off-equipment maintenance on both aircraft. The JB-MDL innovation lab serves as the basis key focal point for developing and using new and emerging technologies that are key to the 305th and 87th Wing's mission. The JB-MDL Innovation lab provided survey results of members who participated in the demonstration on the practical applications and effectiveness of the AV.

Rover

Maren-go provided the AV used in this demonstration. The AV was chosen because of its capabilities to perform for up to four hours while carrying loads up to 440lbs, on or off-road. The AV also possesses collision avoidance, autonomous point-to-point transportation capability with the use of GPS navigation and programmable safety features. Figure 5 summarizes the Maren-go AV that will be used during this study.

Figure 5. Detail of the Rover EV (Maren-go Solutions Corp, 2020)

Procedures

Demonstration Set-up

One essential goals of this study is to assess AV’s application for outdoor operations on the flight line. Applying the technology in real-world environments provides a better understanding of its usefulness and effectiveness (Fragapane et al., 2021). The researcher set up the demonstration locations after discussions with base leadership, subject matter experts, and previous research conducted at JB-MDL. Set-up of the demonstration on an active-duty USAF base required multiple surveys and geo-fencing of bottleneck and accident-prone areas. During all times, the technicians monitored the safety of operations with a following vehicle. The researcher used a modified workflow process depicted in Figure 6. Users will employ the AV Rover in various flight line roles and transport equipment from programmed points of supply.

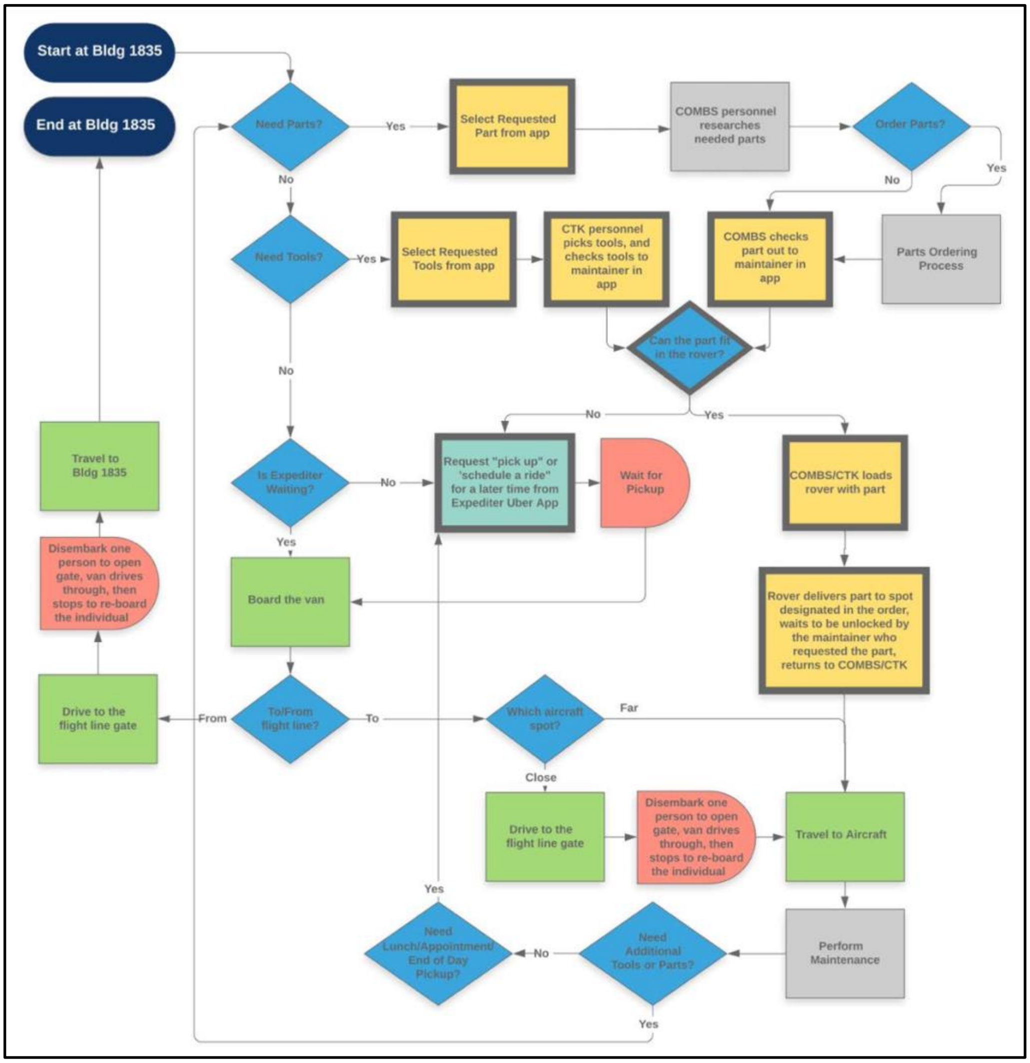

Figure 6. Proposed AV Use Process Flow (Stanton, 2020)

Routing

The researcher selected routes to avoid interferences with active moving aircraft. In many of today's AVs, routing is dynamic, with vehicles connected to a network that adapts to traffic, roadways, and moving obstacles (Hancock et al., 2019; Meldert et al., 2016). The demonstration consisted of predetermined routes on a moderately traveled flight line access road as pictured in Figure 7 and then be tasked to travel between the requested points along the highlighted route. Points 10, 29, and 27 are important because they represent a possible collision zone where 60K cargo pallet loading vehicles are not required to stop. The AV was programmed to make scheduled stops and avoid all potential collisions. The standard stand-off distance of the AV was 3 meters but was extended to 30 meters to allow for greater reaction time.

Figure 7. JB-MDL Way-point Layout

Routing decisions were determined by the researcher, subject matter experts, and base leadership based on discussed safety concerns. The researcher and the subject matter expert surveyed the airfield and maintenance complex to discover bottlenecks where additional precautions need to be taken. The researcher prepared an Air Force Form 4437 Deliberate Risk Assessment approved by the JB-MDL Maintenance Commander, Airfield Operations, Flight Safety, and the base commander.

Exploratory Research Design Method

The overall purpose of exploratory research is to discover something new by working through a topic and developing problems to be further researched (Stebbins, 2012). Exploratory research is primarily used when the topic has not been clearly defined, and the researcher needs to familiarize themselves with the topic (Singh, 2015). Exploratory research seeks to provide additional insight into an area where little is known in hopes of furthering the topic (R. Brown, 2011) Exploratory research provides the researcher freedom to familiarize themselves with the concepts and topic without being too focused on one area of study (Singh, 2015). Exploratory research is often coupled with emerging technologies that provide the researcher flexibility and lack structure and lead to confounding issues. When the purpose of the research is to discover confounding issues, the methodology is most appropriate, as is the case of this study.

Problems with the use of exploratory research in applying emerging technologies are that it lacks an underlying theory, provides inadequate research design, lacks effective measurement, and can be confounding due to the diversity of context (Barnes et al., 1992) Exploratory research may also not provide decision-level results. A significant challenge will be to collect enough data to present results for future studies without limiting AV application. There are also concerns with exploratory research that it may lead the reader to believe the research has produced promising results when it has not (Armstrong, 1970). It is important to note that this criticism focused on searching for data exploration to support a biased conclusion.

This method was chosen because the full scope of applications of AVs on the flight line has not been researched (Hancock et al., 2019; Ma et al., 2020; Meldert et al., 2016) and the application of emerging technologies commonly apply exploratory methods (Ponelis, 2015). The exploratory research design method was utilized because it allows the researcher to test AVs in an application that had not been used (R. Brown, 2011) and provides the researcher the flexibility to discover novel applications of AVs on the flight line. Questions, confounding problems, and discoveries will further enrich AVs' exploratory research on the flight line. The researcher enjoyed the support of Air Force Headquarters level leadership and overwhelming support from the airfield owners that allowed for exploratory research.

Data Collection and analysis

The researcher will collect videos and photographs to display user-case demonstrations. The research will observe and document the performance and applicability of the AV in a variety of task on the flight line. AV data will be collected via GPS navigation data files through ULog file types and be uploaded to Flight Review (https://logs.px4.io/) for compilation and analysis. The AV mission performance will be tracked in Microsoft Excel on a mission log and summarized later in this paper. The researcher will compile the data gathered from the ULogs and analyze it with tables and charts. The researcher used google maps to display and analyze mapping and performance data of the AV. Data for the collection of FOD was attained by certified scales and compared to the 305th Air Mobility Wing FOD collection data.

Strategic Capability Analysis

According to Ansoff, strategic issues are a "forthcoming development, either inside or outside of the organization, which is likely to have an important impact on the enterprise's ability to meet its objectives" (Ansoff, 1980). He further elaborates that an issue can be an *opportunity* to be "grasped in the environment, or an internal *strength* which can be exploited to advantage" (p. 3). The same issue can provide a weakness or missed opportunity if it is not exploited. The strategic analysis provides "determination of thrusts for the future development of the enterprise" (p.3). One could argue that crewless autonomous vehicles and systems are classified as strategic due to their ability to shift future warfighting paradigms.

To determine the subject's strategic capability and answer the provided research questions and conduct a capability analysis, I have captured both the programmatic and contracting processes necessary to access budget resources. This research to address the investigative questions and a previous study conducted on AV at JB-MDL seeks to find if autonomous material handling solutions can augment flight line operations and any secondary benefits and limiting factors. This research will fulfill the capability analysis and user needs. The researcher executed the demonstration at JB-MDL with KC-10 and C-17 aircraft maintenance technicians. The strategic capability analysis includes six steps that have been adapted from Johannesson and Palona's (Johannesson & Palona, 2010) work to assess autonomous material handling vehicles.

Similar work on strategic capability analysis breaks the framework into four broad categories: physical resources, financial resources, human resources, and capital resources but explicitly focused on higher education institutions (Hanif & Tariq, 2014). The adapted Johannesson and Palona model from Ansoff's strategic capability assessment better suits the military environment. Earlier contributions from Ansoff developed a strategic impact assessment for strategic issue management that identified a management framework for early identification and fast response to "important trends and events both inside and outside an enterprise" (Ansoff, 1980). Critics of this model claim it lacks a relational understanding between resources and performance. Ansoff states that his framework is only a starting point to diverge from (Ansoff, 1980). Nwachukwu & Chladkova take the traditional view of strategic analysis of resources as tangible resources (human, financial, organizational, and physical) and intangible resources (reputational, regulatory, social, positional, functional, and cultural) (Nwachukwu & Chladkova, 2019). While this framework provides an understanding of an organization's resources and the impact on strategic capability, it does not assess future impacts and the organization's ability to drive future environments.

Summary

This research employed a modified strategic capability analysis and testing of an AV technology for flight line use. This methodology also included reviewing operational flight line safety documentation to ensure the safe operation of the AV. The researcher observed the AV in the flight line environment and the maintainers' interaction to address the investigative questions and, ultimately, the research question. The next chapter will analyze the demonstration of the Rover covers the results and analysis.

IV. Results and Analysis

Overview

This chapter presents the results of the rover demonstration and addresses the investigative questions. The significance of these results will be shown in the next chapter.

Investigative Question 1

Are autonomous vehicle operations on the flight line safe?

For AVs to operate safely in the flight line environment, they must correctly follow flight line driving regulations and safety precautions. The AV was stopped by the user for undesirable operations 19 percent of the time. It is important to note that 67 percent of undesirable behaviors resulted in successful re-testing after navigation way-points were adjusted or equipment was reset, and 100% could have been with additional way-points. Still, the researcher chose not to re-attempt the mission due to time limitations. It is worth highlighting that rain, high winds (greater than 35K), or overcast were present on 66 percent of the incomplete runs. Additional testing on weather impacts should be conducted as the literature review indicates inclement weather can have undesirable responses. An area of concern is points 10, 29, and 27 in figure 8, where the 60K cargo pallet loading vehicles are not required to stop during operations. The AV executed all appropriate flight line stops and stopped for a crossing 60K vehicle, as seen in Figures 8 and 9 and then continued along its route.

Figures 8- 9. Points 10 29, 27, and 60K Loader Crossing Area with AV making a safe stop

As the missions progressed and the way-points were further refined, the AV performed more successfully.

Investigative Question 2

What are the uses of autonomous vehicles on the flight line?

The exploratory research method allowed the researcher to employ the AV in applications other than originally pursued. For example, the original intention was to utilize the AV in material handling to augment the expediter role. The AV was modified and successfully towed a FOD collection attachment (See figure 10) which is a task that is carried out weekly by maintenance personnel with a flight line vehicle.

Figure 10. AV with FOD collection attachment

The AV was also modified to pull small Aerospace Ground Equipment (AGE) and deliver it to the requested location. Figure 11 demonstrates the AV with the attached oil dispensing cart. When the AV executes AGE missions, it releases AGE technicians to conduct critical repair and inspection items on-ground equipment. JB-MDL, for example, employs 1-2 AGE drivers 24 hours a day to deliver equipment.

Figure 11. AV with Oil Dispensing Cart

The AV was used to transport various tools and equipment throughout the flight line of up to 400 lbs. and simultaneously transport equipment while executing other tasks. It also maneuvered in and out of a C-17 to demonstrate quick roll-on and roll-off capabilities. To conduct autonomous operations in a new environment, the destination way-points and mission assignments must be added before the debarkation.

Figure 12. AV C-17 Roll-on Roll-off

Investigative Question 3

Are autonomous vehicles on the flight line effective?

As discussed, the Rover successfully transported parts and equipment from the CTK to the appropriate work centers; Table 1 summarizes the AVs utilization that can augment an expediter's tasks.

Table 1. Rover Utilization Tasks

Task	Effective Rate	Expediter Task?
Equipment	*53%	Y
FOD	100%	Y
AGE Transport	100%	N

*Desired AV behavior can achieve 100% with additional set-up and time.

The AVs speed can match flight line vehicles used by the expediter. The AV can fulfill 35 percent of a C-17 expediters utilization and 43 percent of a KC-10's expediters utilization (Stanton, 2020), freeing them for additional value-added tasks. The AV conducted 32 missions and exhibited the desired response the first time 53 percent of the time, as seen in Table 2. Mission success was achieved when the AV was able to execute its mission without any human intervention.

Table 2. AV Mission Summary

Missions	No human intervention required	Human intervention required	Pauses due Undesirable behavior	Full autonomous Rate	Undesirable behavior pause rate	Safety Re-test success rate
32	17	15	6	53%	19%	67%

Causes for human interventions are summarized in Table 3. When the AV could not execute its mission and required human interventions the GPS way-points were adjusted or reset. The AV was paused when it began to drift outside the driving lane. Causes of the undesirable behaviors included excessive GPS drift leading to way-point adjustments, yaw errors, failing to start or stop, and circling the way-point. Inaccurate way-points caused the majority of failures, and after each failure, the mission way-points were adjusted. The AV was successfully able to complete a mission across the entire flight line access road, and with additional set-up time and research time, future users could achieve near one-hundred percent results.

Table 3. Human intervention Summary

Cause	**Quantity**
Drift (Way-point adjustments)	9
Could not reach the way-point (circled way-point)	2
Yaw Error	1
Failed stop	1
Uncommanded Stop	1
Equipment	1
Total	15

The Rover demonstrated that it could travel at the required speed on the flight line. During an interview with an aircraft maintainer, they commented that it was helpful to track where the AV was with the equipment to better plan their work. The most encouraging discovery was the application of the AV to execute FOD collection tasks. Table 4 summarizes the results of the AV FOD collection versus traditional FOD walks on the flight line. The AV produced a 2,642%

increase in FOD collection versus traditional FOD walks and a 26,164% increase in pounds of FOD collected per hour. The applications for FOD collection are highly effective.

Table 4. FOD Collection Results (One Squadron)

Aspects	FOD Walk	Rover 1 and 2	Percent Difference of Rovers vs Humans
Personnel Used	33	2	6.1%
Area Covered %	100%	10%	10.0%
Debris Collect Lbs	0.28	7.4	2642.9%
Man-Hours	49.5	0.5	1.0%
pds/hr	0.005656566	14.8	261642.9%

Investigative Question 4

Does companion software eliminate bottlenecks, or does it increase them?

The cellphone add-on application was not tested and should be considered for future study. The researcher used excel spreadsheets and radios to command and control the AV. The use of a phone-based application would replace the need for radios and spreadsheet tracking. Broader widespread dissemination of the application to flight line personal would have eliminated the need for intermediate communications between the expediter and the location placing the order in the AV. A future demonstration including software synchronization tools will address unnecessary communication and efficient control of the AV.

Research Question

The research question asks, can an autonomous vehicle work on the flight line? Assessing each of the investigative questions reveals that an AV can operate on the flight line. Still, there is room for improvement primarily centered around establishing base infrastructure that supports autonomous operations and assessing the add-on software application. Each investigative question was addressed and is summarized in Table 5.

Table 5. Analysis of Autonomous Vehicles on the Flight line

Use of autonomous vehicles on the flight line				
Investigative Questions	Red	Yellow	Green	**Unique Considerations**
Safe Operations		**X***		The vehicle employed one GPS control. Greater accuracy and efficiency can be achieved with RTK-GPS or lidar line painting.
Uses of AVs on the flight line			**X**	The AV was able to be modified during the study and employed as a tow vehicle for Foreign Object Debris (FOD) equipment and Aerospace Ground Equipment (AGE).
Effectiveness of AVs on the flight line		**X***		*With the improvements of GPS, the effectiveness of the AV will greatly increase.
Software bottlenecks		**X***		The cellphone application was not able to be tested—the researcher used excel spreadsheets and radios to dispatch the AV. The use of a phone-based application would replace the need for radios and spreadsheet tracking.

Strategic Capability Analysis

The ability to successfully operate an autonomous vehicle on the flight line instinctively leads the reader to ask, so what? Ansoff describes strategic opportunities as developments that are likely to impact a unit's ability to meet its objectives (Ansoff, 1980). This use-case has demonstrated that with future refinements of requirements, AVs can be exploited as a strategic capability to be used in multiple roles on the flight line and in aircraft warehouses. The ability to grasp the autonomous environment by synchronizing the command, control, and communication (C3) systems and exploiting AV's capabilities will prove how successful units will be. With little effort, AVs can be classified as strategic because of their ability to shape future wars through reduced risk and synchronization of command, control, and communication in the battlespace.

An element of the strategic assessment is capturing the costs required to fund and sustain the capability. Specific to the use-case, future opportunities to establish a sustainable testbed will require four to seven thousand dollars a month for five supported vehicles. To improve the effectiveness of the AVs, infrastructure investments such as Lidar systems and single command and control suites of the AVs will be required.

The demonstrated use of an AV on the flight line that started with material handling solutions was adapted to towing FOD collection equipment and AGE equipment and can be adapted to cargo pallet moving equipment and tow vehicles (Bobtails) for snow removal or towing. This technology possesses wide-ranging effects on several stakeholders in the Air Force community that operate on the ground.

Summary

This chapter presented the results of the rover demonstration and addressed the investigative questions. The conclusion and recommendations for the use and improvements of AVs is in the next chapter.

V. Conclusion and Recommendations

Overview

The purpose of this exploratory research study is to discover if autonomous vehicles can work on and within the USAF flight line infrastructure. An AV was deployed at JB-MDL, NJ to document the limitations and use-cases. The research questions and investigative questions have been addressed.

Conclusion

The Air Force has never conducted research to demonstrate the use of AVs on the flight line, and the results were an extensive development of the problem set required to further the use of AVs. The study revealed that AVs could operate on the flight line safely, in a useful and effective manner, but was unable to test the efficiencies or bottlenecks or add-on mobile software.

From the literature review, an effective AV meet the user's needs and is cost-effective, sustainable, and adaptable (Gružauskas et al., 2018). Effective AVs should also result in some measured increase of efficiencies or productiveness that will decrease costs. (Bagloee et al., 2016). In the second quarter of FY21, JB-MDL conducted weekly FOD walks with an average attendance of 86 personnel and collected an average of 8.07 pounds of FOD per week (*2Q FY21 FOD Report*, 2021). If the average USAF maintenance technician pay is $30.06/hour (*U.S Air Force Aircraft Mechanic Hourly Salaries in the United States*, 2021) the return on investment for utilizing the AV for FOD collection will result in $41,962 per year. The savings is calculated by taking the labor-hour savings of $135,029 per year and subtracting the annual cost of leasing five AVs at $82,680. Utilizing the AV for FOD collection also resulted in a greater than 261,000% increase in pounds collected per hour (See table 3). FOD walks should not be completely abandoned, but AVs are ideally suited for tasks such as FOD collection. The cost savings are summarized in table 6.

Table 6. Labor-hour equivalent Savings

	Month	Year
Personnel Savings	$ 10,386.89	$ 124,642.63
Rover Cost	$ 6,890.00	$ 82,680.00
Total Savings	$ 3,496.89	$ 41,962.63

Efficiencies gained from the FOD collection alone will return time to those who work on the flight line and result in greater FOD collection. The AV will make more than $3,000 per month, and based on the literature review, the USAF should pursue it for this type of task. Furthermore, the reduction in FOD on the flight line will continually prevent a possible mishap or ingestion of foreign debris into an engine, especially considering aircraft with lower engines such as the KC-135R and F-16.

In addition to FOD collection, the AV can have other implications. The AV can also be adapted to executes AGE missions. When the AV tows AGE it releases 1-2 technicians every 24 hours to conduct critical repair and inspection items on-ground equipment. The AV was used to transport various tools and equipment across multiple points with 105 pounds. The AV also maneuvered in and out of a C-17 to demonstrate quick roll-on and roll-off capabilities carrying a 45-pound weight.

It is important to highlight the limitations and problem areas discovered to be addressed in future research. The limitations experienced were separated into three categories; AV technology, processes, and base or infrastructure. The AV was limited to a single GPS receiver until the last day. After the second GPS receiver was installed, no noticeable improvements were experienced. The AV required extensive set-up using the GPS for navigation in congested areas with other drivers. Additional training and customer support will be required for casual users of the AV's navigation and programming features until a cadre of subject matter experts is developed to train additional users. Users were required to frequently adjust and re-position way-points after each mission. This process was labor-intensive and, at times, and induced additional errors. The AV design was limited in weight, battery life, and functionality but able to prove that AVs can operate extensively in various roles on the flight line.   Future users must define specific requirements that will allow the hardware and software integrators to develop the most beneficial AV for their mission sets.

The initial restraint in process limitation is that autonomous operations are considered non-standard and are outside of current Air Force policy. Once approval was gained to operate the AV on base, the researcher had to work through levels of safety assessments, restrictions, and risk areas to demonstrate AV use successfully. While these barriers are necessary for risk reduction and ensuring safety, they inherently restrict operations. A balanced approach that avoids absolute restrictions such as “no-drone zones” should be perused. These limitations can easily be remedied with a pre-defined test area and proper frequency management that allows the exploration of AV capabilities in near real-world conditions. The current base policy does not support autonomous operations and must be become part of the policy planning cycle to increase effectiveness.

Within the base infrastructure, there is no ability to synchronize command, control, and communication with base, port, and maintenance operation centers at the tactical level of control. To effectively control a fleet of AVs, a meshed communication and control network must be in place. The research revealed that in areas where multiple large hangars disrupt the GPS signal, the accuracy of the AV is reduced from less than one meter to three meters. Figures 12 and 13 illustrates areas where GPS disruptions occurred.

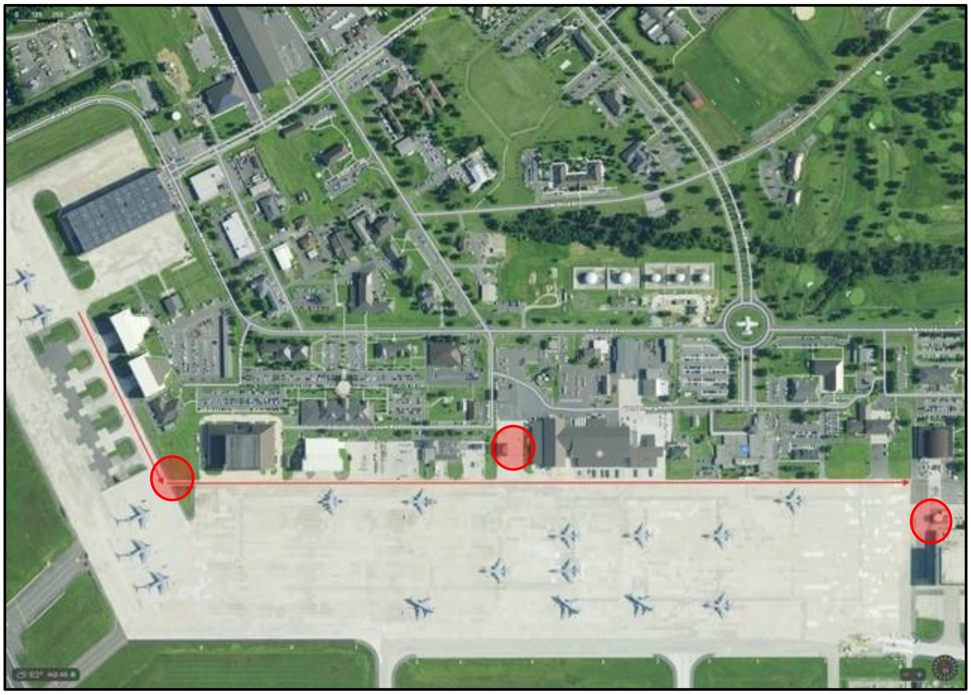

Figure 13. GPS Bottleneck Locations

Figure 14. GPS Bottleneck Locations

It is important to note that this study was conducted without frequency analysis or data of the surrounding area. It is recommended that frequency data be collected and analyzed to limit or rule out interference in the area of operations.

While not directly experienced, base safety members voiced concerns about network security and potential software challenges. Network security is indeed a potential issue that must be part of future requirements (Bagloee et al., 2016).

Significance of Research

The strategic capability analysis and AV demonstration on the flight line illustrated that an autonomous vehicle could transport material handling solutions and be used for other ground tasks. While used widely in other environments as described in the literature review, AV technology has not been implemented in USAF flight lines. The research outlines successful use cases and further scopes the AV problem set on the flight line to be further addressed with additional testing. Additionally, testing will drive requirements analysis and policy changes as the environment is shaped to not only accommodate but exploit AV technology.

This capability can be adapted for future capabilities used for inspection, personnel transport, fuel and ammunition delivery and loading, maintenance, diagnostics, and troubleshooting technologies to augment our workforce. Although base security was not attempted in the study, the AV is well suited to conduct perimeter security and surveillance due to its off-road capabilities, freeing up Security Forces defenders for essential value-added tasks. This technology, if applied deliberately, can shape future policy and reduce risk to force. This study provides USAF senior leaders and acquisition managers with additional solutions and applications for current and future technologies. With greater understanding and improved infrastructure and policy inclusion, AVs will gain greater efficiencies not only on the flight line but base operations and combat operations.

Recommendations for Action

The recommendation to pursue a suite of Maren-go-like AVs is based on labor-hours savings and reviewed literature suggesting that AVs are more effective in FOD collection or snow removal type roles. A balanced approach to policy development and safety that avoids absolute restriction should be persued. Greater confidence in autonomous technology can be achieved with a pre-defined test area or 'lighthouse' facility that allows the exploration of AV capabilities in near real-world conditions. To effectively control a fleet of AVs, a synchronized C3 system must be in place. It is also recommended that the base conduct a frequency analysis in the AV test area. Below is a list of recommended items for action.

Table 7. Recommendations for Action

	System	**Infrastructure**	**Processes**
Immediate	Execute leasing option for four-five AVs at $5-7K per month for FOD collection, and to further explore and refine autonomous capabilities and gaps.	Conduct frequency survey to identify signal bottlenecks and areas additional navigation systems.	Pursue JB-MDL and the EC as an autonomous operation "lighthouse" to conduct further technology research.
			Research policy restrictions and limitations that inhibit and prohibit autonomous operations
			Establish a cadre of autonomous vehicle subject matter experts (Ex., Maintenance, Flight, Security Forces, Transporter, Supply, Communications personnel).
Secondary	Provide future vehicle user requirements to include flexible systems.	Establish synchronized command and control, communications system, and collision avoidance network across the base.	

	Enable remote cameras on Rover to verify obstructions or base	Implement RTK-GPS and Lidar painting along flight line access road or delivery points where GPS signal is weak (AGE, 605th CTK) after a properly conducted frequency survey.	

To execute its mission, maintenance organizations must have appropriately trained, equipped, and resourced teams. As the Air Force struggles with finding the right fit of properly trained flight line technicians, utilizing our Airman in value-added roles is more urgent than ever. The future of aircraft maintenance requires solutions and processes that maximize Airman's capabilities and alleviate redundant, non-value-added tasks from operations. The researcher demonstrated that an AV could work on and within the United States Air Force flight line infrastructure to free flight line personnel for value-added roles. The study revealed that AVs could operate on the flight line safely, in a useful and effective manner, and provide some labor-hour cost-savings benefits when applied in FOD collection tasks. More importantly, the study results were an extensive development of the problem set required to fully employ autonomous vehicles in flight line or aerial port environments. A 'lighthouse' testbed should be established at JB-MDL for further testing that can support the development and sustainment of AVs DoD-wide.

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1. REPORT DATE *(DD-MM-YYYY)* 04/06/2021	**2. REPORT TYPE** Graduate Research Paper		**3. DATES COVERED** *(From – To)* July 2020 – 4 June 2021
4. TITLE AND SUBTITLE Autonomous Vehicles for Flight line Use			**5a. CONTRACT NUMBER**
			5b. GRANT NUMBER
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Sollee, Joshua P. Major, USAF			**5d. PROJECT NUMBER** N/A
			5e. TASK NUMBER
			5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/ENS) 2950 Hobson Way, Building 640 WPAFB OH 45433-8865			**8. PERFORMING ORGANIZATION REPORT NUMBER** AFIT-ENS-MS-21-J-065
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) BG Linda S. Hurry HAF/A4L 4A1062B Pentagon, Washington DC 20330 Linda.hurry@us.af.mil			**10. SPONSOR/MONITOR'S ACRONYM(S)** HAF/A4L
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A.APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.			
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14. ABSTRACT The purpose of this proof-of-concept study is to discover if autonomous vehicles (AV) can work on and within the United States Air Force (USAF) flight line infrastructure to free flight line personnel for value-added roles. An autonomous vehicle was deployed to Joint Base McGuire-Dix-Lakehurst (JB-MDL), NJ, to document the limitations and uses and sought to answer; can an autonomous vehicle work on the flight line? The study revealed that an AV could operate on the flight line safely, in a useful and effective manner, and provide some labor-hour cost-savings benefits when applied in foreign object and debris (FOD) collection tasks. The study results were an extensive development of the problem set required to fully employ autonomous vehicles in flight line or aerial port environments. A 'lighthouse' testbed should be established at JB-MDL because of the cross-service environment and access to the Air Mobility Command's (AMC) Expeditionary Center (EC).			
15. SUBJECT TERMS Autonomous Vehicles, Flight Line, Value-added, Maintenance, Aerial Port, Material Handling			

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Lt Col Jason Anderson AFIT/ENS
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)*
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Standard Form 298 (Rev. 8-98)
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