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SafeTug
Semi-Autonomous Aircraft Towing Vehicles

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1. Introduction

Congestion at airports is recognized as one of the most prominent problem areas in the international airspace. In particular, increasing the capacity of surface area used for taxiing is a major logistical challenge. Traditionally, airports address the capacity problem through the addition of runways and taxiways. This solution has the unwanted effect of increasing the complexity of air terminal operations. This penalizes the efficiency of the system by adding to human workload, thus restricting the potential benefits of the surface expansion. The increased complexity also increases the risk of human error, resulting in potentially hazardous situations. In addition, the increasing number of taxiing aircraft will contribute significantly to an increase in fuel burn and emissions. The quantities of fuel burned as well as different pollutants, such as carbon dioxide, hydrocarbons, nitrogen oxides, sulfur oxides and particulate matter, increase with aircraft taxi duration, and also vary with throttle setting, number of running engines, and pilot and airline decisions regarding engine shutdown during delays. *The practical difficulties of increasing capacity through airport expansion introduce the desire for enhanced airport ground movement efficiency by the* ***intelligent use*** *of the existing resources.*

1.1. Current Practice

Aircraft depend on their main engines or human-driven towing vehicles during departure or arrival ground operations. The departure procedure consists of 4 phases: pushback, engines-start, taxi-out, and engine warm-up. In the arrival procedure, there are three phases: taxi-in, engine cool-down, and shutdown.

Figure 1 TaxiBot Towing Vehicle

There are a number of improvement areas identified for surface operations:

1. Increasing efficiency in operations, including higher precision navigation and finding alternatives to voice communication between tower and cockpit.

2. Reducing the environmental impact in the form of pollutants: for example, taxiing at airports using main engines results in emissions of around 18 million tons of CO2 per year.

3. Economic; in 2012 taxiing at airports using main engines was forecast to cost airlines around $7 billion in fuel cost, in the form of fuel burn, inefficient engine operations in idle setting, break wear due to increase during stop and go taxiing, and the risk of foreign object damage due to engine suction.

1.2. Proposed New Taxi Concepts

Figure 2 Electric Taxi

The economic pressures and increasing environmental awareness have recently fostered the development of new taxi operation technologies and procedures. There are three basic approaches to engines-off taxiing being proposed in industry, all of which have strengths and weaknesses. The most obvious approach is a concept called "Operation Towing" (Wollenheit and Muhlhausen 2013), which simply involves the use of human-driven aircraft towing vehicles. Operation towing has the following advantages:

1. They require little if any logistical or operational changes to current airport operations: human drivers of towing vehicles exist now and can be put into service easily to implement full towing operations.

2. They lead potentially to reduction of workload for the flight crew, which they can use more efficiency for other purposes, such as engine warm up or safety checks;

3. There is an increase in redundancy for taxi safety due to an extra pair of eyes monitoring the surface.

A disadvantage of this approach is the additional complexity in operations in the form of added coordination between pilots, tower controllers and towing vehicle drivers. In particular, more human voice communication for the purpose of coordination is required. As noted in a number of studies (e.g. Brinton et. al. 2002), voice communication is inefficient as a means of coordination due to the capability to deliver only a single instruction at a given instant, the potential for miscommunication of the spoken word, and frequency congestion.

A promising variation of Operation Towing is the "TaxiBot" (Richard 2013), in which a tug driver manages the pushback phase of the departure, but the aircraft pilot remotely controls the tug movements for taxiing to the runway (Figure 1). This removes, at least partially, the added need for additional human coordination of operational towing, but introduces added pilot workload, and new safety issues may emerge with respect to the ability of the pilot to effectively control an external towing vehicle. Furthermore, this solution incurs the overhead of requiring additional flight controls into the cockpit display for operating the tugs. Finally, using TaxiBot for arriving aircraft would involves the need for human tug drivers to meet the aircraft at the runway, and it is hard to see the advantages of transferring control from tug driver to pilot in the case of arrivals. So TaxiBot is in fact a hybrid of Operation Towing and pilot-driven towing, which again adds to the complexity of procedures. TaxiBot has only been used for departures, and therefore is only a partial solution to the overall problem of enabling engines-off taxiing.

A third promising development is the use of electrically powered landing gears for medium-sized aircraft in civil aviation ("Electric Taxi" or 'Wheel Tug"), again pilot-controlled (Tarantola 2013). This approach eliminates the potential control and complexity issues associated with TaxiBot, because the pilot is not in this case controlling a separate vehicle, but rather merely a separate engine on the aircraft. This solution also eliminates the added surface traffic incurred by separate towing vehicles. However, this approach again provides only a limited solution to the general problem, insofar as the auxiliary engines are not powerful enough currently to pull larger airplanes. In addition, this solution requires airlines to retrofit their fleet with the new engine, which are significant investments.

1.3. Autonomous Taxiing Concept

The contribution of this report will consist of proposing a concept and presenting a case for surface taxiing operations based on 'self-driving' towing vehicles. *By autonomous engines-off taxiing, we mean a towing vehicle that will, on command, autonomously navigate to an assigned aircraft, attach itself, tow the aircraft to an assigned location (a runway for departures, a gate for arrivals), autonomously detach itself, and navigate to an assigned location, either a staging area or to service another aircraft.*

To our knowledge, no industrial effort is currently developing self-driving vehicle technology needed to realize engines-off taxiing. We suspect the main reasons for not considering this option are the changes that must be made to airport operations in order to integrate autonomy. These changes include more surface traffic (unattached self-driving tugs will increase the density of surface traffic), different procedural protocols (e.g., tug navigation decisions will replace communication between controllers and pilots), and the complexity of human-machine interactions (ground controllers, pilots and self-driving tugs will need to operate effectively together).

The case for autonomous engines-off taxiing is summarized as follows. First, recent advances in self-driving automobiles make it technologically feasible to apply this technology for the purpose of taxiing planes to the runway from the terminal gate and vice-versa. Arguably, deploying self-driving vehicles for this purpose offers fewer technical challenges than deploying them on roadways and highways. On the one hand, routes between gates to runways and runways to gates are typically pre-determined, with little or no possibility for alternatives. In addition, to ensure safety, constraints on taxiing operations are rigid and unambiguous. Rules of the road such as separation constraints between taxiing aircraft and those governing right-of-way at intersection points are clearly documented and enforced by ramp and ATC controllers. These rules and procedures reduce the overall uncertainty in the operational environment and therefore potentially simplify the models that would need to be employed by self-driving vehicles.

1.4. Autonomous Taxiing: Requirements and Challenges

In order to effectively transform taxiing operations to incorporate autonomous towing vehicles, the following four requirements must be met:

1. The tugs must be safe: they do not run into structures, planes or people; tugs must also follow rules of the road e.g. follow the center line.
2. The impact of their incorporation into normal operations is perceived to be minimal; humans don't need to change their behavior (much);
3. Changes to the airport infrastructure are minimal i.e., there are no major redesign of taxiways or ramp areas; and
4. Their use improves surface logistics, and their utilization makes humans better at their jobs.

These requirements lead to three classes of challenges in integrating autonomy into airport surface operations:

1. Technical challenges: autonomous towing must accommodate large unpredictable, real time variation in the environment; must achieve customer-acceptable reliability levels, and provide intrinsic safety of use and operation;
2. Economic challenges: tug-based operations must achieve the required affordability (ideally, payback within 12 months), providing no external hidden costs to the customer, and provide a robust business model; and
3. Social challenges: if labor replacements are involved, then the use of autonomy must provide an equivalent or greater benefit to some portion of the labor pool to offset the potential job loss; furthermore, they must operate in a way that feels common and familiar to humans, and must be perceived as completely safe, simple and non-intimidating.

In identifying the autonomy capabilities for the automated towing vehicles, the following constraints drive the design considerations:

Safety Drivers

- Human – Autonomous Tug must be safe to operate near people
- Equipment – Autonomous Tug must not pose a physical (mechanical, electrical, etc.) threat to infrastructure, vehicles, etc.
- Continuity– Autonomous Tug must not be disruptive to existing procedures for ground operations

Cost Drivers

- Up-Front – Applique must not have a high cost of entry
- Recurring – Applique must not be financially burdensome over time

- Reversibility – Applique must be able to be completely removed and tug restored to normal manual operability

Effectiveness Drivers

- Logistics Improvement – Measurable positive impact to logistics
- Cost Improvement – Measurable reduction in cost related to fuel consumption by aircraft while on the ground.

2. Overview of Technical Approach

The introduction of autonomous towing vehicles into surface operations significantly impacts how humans (specifically ramp controllers, ground personnel and pilots) perform their work. Consequently, making a strong case for autonomous taxiing requires addressing the challenges of human-machine interaction, hybrid human-machine control, incremental deployment strategies, and minimizing changes to existing infrastructure and procedures (Bayouth, Nourbakhsh and Thorpe 1997). The solution we propose views the challenge to be one of *providing logistics rather than autonomy* (borrowing an adage used by (Aethon 2013)). Logistics is the problem of coordinating a complex operation involving many people and machinery. Our solution involves the use of autonomy, but must also address broader issues involving human-autonomy interaction and complex motion planning.

2.1. Technology Components

We propose a three-pronged architecture for integrated taxi operations using self-driving towing vehicles combining enhanced automated decision support tools, human-machine interfaces supporting human awareness and supervision of autonomy, as well as robotic technologies for autonomous sensing, navigation, communication and control. The work performed during the course of this research consisted of the following:

1. A rigorous and systematic study of current surface operations at major US airports, consisting of interviews with pilots and tower operators;

2. A complete case study of autonomy capabilities in sensing, control and communication required for safe and efficient towing operations;

3. Software development in towing vehicle route planning and scheduling in order to address the complexity of surface operations resulting from the addition of autonomous tugs; and

4. The use of a fast time simulator (described in more detail below) to measure the effects of the introduction of autonomous towing operations.

In addition, we explored various strategies for the incremental introduction of autonomy into surface operations, to reduce the impact of infrastructure changes and allow for the evolution of trust and confidence.

2.2. Performance Metrics

In evaluating the impact of autonomous engines-off taxiing, we have identified four performance metrics:

1. *Efficiency*, primarily in the amount of delay in taxi time and maximizing throughput;

2. *Complexity of logistics*, primarily in the form of workload for flight crew, tower personnel or ground crew;

3. *Safety* in the form of things like maintaining separation constraints and avoiding potentially dangerous events such as runway incursions; and

4. *Environmental and economic benefits* through reduced fuel emissions and reduced maintenance costs through less wear on airplane engines.

3. Tug Dispatching, Scheduling, and Analysis

Optimization of airport surface operations can be classified into the following sub-problems:

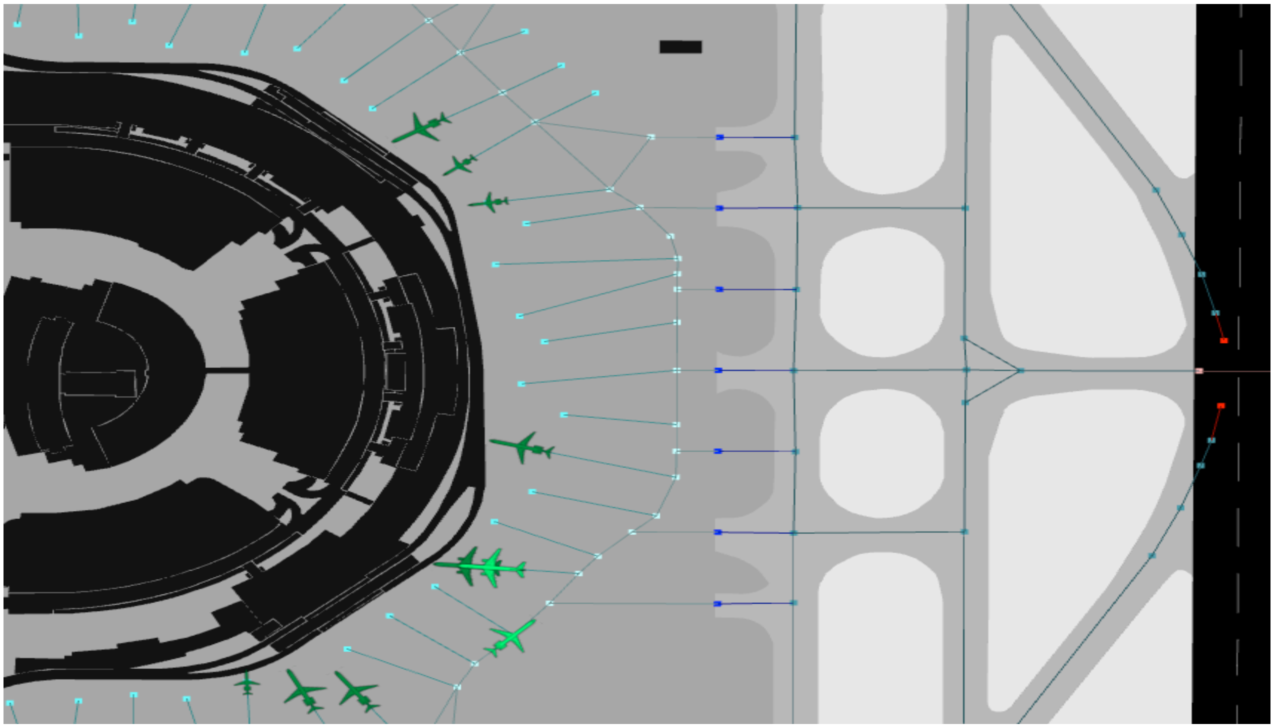


Figure 3. Graphical Diagram of Dallas Forth Worth Airport Used for Simulation

runway sequencing and scheduling (Rathinam et. al, 2009); spot or gate release scheduling (Malik, Gupta and Jung 2012); gate allocation (Cheng, Sharma and Foyle 2001) and taxi route planning and scheduling (Visser and Roland 2003). Surface movement optimization is NP-hard (Reif 1979). Several types of constraints are involved, including push-back times, taxiway layouts, and runway and taxi-way separation. Planning is dynamic, with aircraft continuously entering and leaving the planning space, and replete with uncertainty and unexpected events. These complexities and the dynamic nature of the environment motivate approaches to automated planning that require reduced computational overhead while achieving useful results.

Surface planning with autonomous tugs is viewed here a centralized process, performed by a planning tool used by ramp controllers, or tower (ATC) operators. The tugs themselves don’t decide where to go or how to get there; they only control their speed to keep safe and adhere to separation constraints on the taxiway.

3.1. SARDA Decision Support Tool

The overall approach to planning and scheduling tug-based surface operations is an extension of the Spot and Runway Departure Advisor (SARDA) approach (Gupta, Malik and Jung 2012). The SARDA scheduler addresses the highly dynamic and uncertain planning environment by a multi-stage process. The next paragraphs summarize this process.

3.1.1. SARDA Architecture

An airport surface can be represented graphically with nodes, representing locations (in terms of *x,y* coordinates) of gates, runway entrances, spots, or other intersections; and edges, representing traversable surface area. Figure 3 shows part of the Dallas Fort Worth International airport (DFW) as a graph. Traverse time between pairs of nodes is captured as a cost assigned to edges.

The scheduler pre-computes the shortest path routes between every pair of nodes using the Floyd-Warshall all-pairs shortest path algorithm, and stores it as a predecessor matrix (Cormen 2001). This matrix is invoked during scheduling time to retrieve routes for tug dispatching and aircraft taxiing.

A subset of nodes in the graph are designated as 'tug depots' that provide a re-charging station and designated locations for dispatching idle tugs. Tug depots should be strategically placed along the surface to reduce the time between dispatching an idle tug and reaching its assigned aircraft for attachment. Tugs can also be dispatched from locations other than depots; for example, a tug might have completed a towing operation to one gate, and be then dispatched to a near-by gate for the next departure towing task.

The SARDA scheduler contains two main components: a runway sequencer and scheduler, and a spot and gate release scheduler; to this system, we add a third component, a tug dispatcher. The spot and gate release scheduler selects times for pushback from the gate, and times for releasing the tug/aircraft for entry into the taxiway (the spot is the entry point into the taxiway from the ramp area). A *tug dispatcher* is a kind of resource scheduler: given an available tug, and an aircraft that needs to be towed, the dispatcher assigns the tug to the aircraft, and generates a shortest-path route for the tug to navigate to reach the assigned craft. Ordering the available tugs to determine the most efficient allocation can be decided using different criteria. We currently use a simple shortest distance criterion: the available tugs are ordered by distance between tug and attachment point (i.e. gate or runway exit), and the one with the smallest distance is assigned.

Figure 4 shows the scheduling cycle and system components. The inputs to the scheduler consists of the current snapshot of the airport (the current locations of each active tug on the surface), scheduled push back and arrival times for the next 15 minutes, and various constraints such as aircraft-specific parameters and separation constraints. Because of the uncertainty in

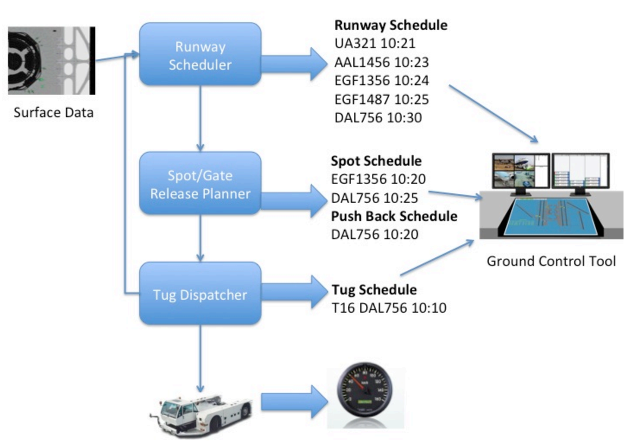


Figure 4. SARDA Architecture with Tug Dispatching

surface dynamics, these inputs are refreshed every 10 seconds. To control the number of changes made to the outputs of the schedule, a 'freeze horizon' is imposed which precludes major changes to be made to the current schedule.

The outputs of the scheduler are three schedules: a runway schedule, a spot and pushback schedule, and a tug schedule. Not depicted in the figure is the fact that the scheduler also generates routes (sequences of nodes) from the shortest-path matrix. The routes or release times are communicated to the tugs, which are considered the 'auto pilot' for pushback and taxiing.

The times computed by the scheduler represent each vehicle's earliest possible arrival time at each node. However, this set of routes may contain numerous conflicts (separation constraint violations). To resolve such conflicts, the system contains a flow model and a network event simulator to model arrivals at nodes representing intersections, and to determine the amount of time that aircraft must hold at current locations to maintain separation requirements, and to ensure other safe conditions (e.g. at intersection crossings, or to maintain wake vortex separation). The flow model assumes conflict avoidance on the surface to be the combined responsibility of the controller and tug. The controller identifies spatial violations in the schedule such as aircraft approaching head-on. The tug determines possible conflicts at the node it is currently approaching, and adjusts its speed accordingly. Together, the scheduler and de-confliction model approximate the taxi routings and resource utilization (gates and runways) that are most likely to be used by tower controllers at DFW.

3.1.2. Tug Dispatching Algorithm

The tug dispatching problem is the following: given a set of idle tugs, and a set of aircraft that need to be towed, assign a tug to each aircraft. The cost function to be minimized is based on two criteria. The first criterion is the overall delay at the gate due to waiting for a tug to arrive. The second criteria is the sum total of times the fleet of tugs is idle. The intuition in the cost function is that idle time is time that the tugs are simply adding to the surface traffic of the airport, which reduces the efficiency of operations.

For the experiments described below, we used a fairly simple greedy algorithm, based on the geometric distance between tug and gate. For each aircraft waiting to be serviced, we first order them in terms of an indicator of the duration they have been waiting for service, which is the difference between the current time and time the aircraft was first ready for service. This ordering will help to reduce the overall waiting times of aircraft. Then, the algorithm iterates over the set of aircraft, and for each aircraft, orders the set of available tugs with respect to shortest distance between each tug and the aircraft. The algorithm choses the tug that is closest in distance.

As with most greedy algorithms, this one is sub-optimal. It is easy to come up with scenarios in which non-greedy assignments will result in overall lesser cost solutions. For future work more sophisticated algorithms for dispatching will be developed.

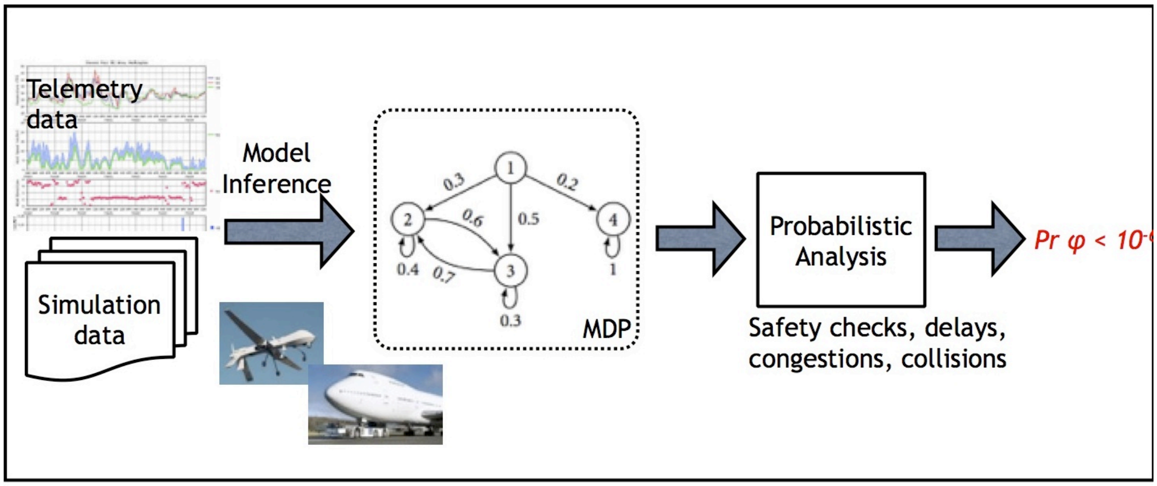


Figure 5 The Stages of Probabilistic Analysis

3.2. Predictive Probabilistic Analysis for Safe Tugs Operations

The goal of this component is to build "behavioral models" of surface operations (for both tugs and airplanes within a specified airport). Such models contain key information that enable analysis with respect to safety, delays, throughput etc. We plan to use these models in a predictive way. For example, one can use such models in the dispatcher to optimize its decisions with respect to minimizing delays in taxiing and avoiding congestions. We build these models automatically from telemetry data, log files and simulation data available from previous or similar operations at the airport.

Our models are Discrete-Time Markov Chains (DTMC), i.e. automata labeled with outgoing probabilities on their transitions. We infer these models from logged data, which typically consists of a time series; each step encodes the value of the states observed at each time step. The states of the inferred model then represent "abstractions" of the state reported in the log file and transitions in the model correspond to the time steps in the log file. The abstraction is defined by the user and it depends on the properties of interest. The log data is discretely sampled, in some cases many times per second, therefore it is necessary to select a resolution to allow for more realistic state transitions and to prevent state space explosion. The probability distribution for a particular state is estimated by computing the ratio between the number of traversals for each outgoing transition and the total number of traversals of the transitions exiting states; this corresponds to the maximum likelihood estimator for the probability distribution at that state.

In particular we have implemented a "grid" abstraction as follows. We divide the airport surface in a grid and we keep "count" of vehicles (airplanes, tugs) in each grid. We have developed a prototype tool (written in Java) that builds models at different levels of abstraction. The models can be visualized (via DOT files) and also analyzed using the PRISM and UPPAAL model checkers.

Example analysis results are as follows: for a log recording the positions of more than 30 tugs and airplanes each second for 70 minutes of activity , we analyzed 123 MB of data in less than 5s. The generated models have 75 states (10x2 grid abstraction) and 96 states (4x4 grid abstraction), respectively.

Example properties analyzed with PRISM include:

- "The probability that less than 30 tugs/airplanes are present in quadrant 0 within the first 50 time units (seconds), is less than 0.6"
- "What is the probability that more than 33 tugs/airplanes are present in quadrant 0 within the first 300 time units (seconds)?"

For future work, we plan to refine our models to distinguish between arrivals and departures, create a more detailed model with a finer grid, use random testing to bootstrap the learning. We also plan to use the model in the dispatcher to minimize delays in taxing, avoid congestions and maximize throughput. Another area that we plan to investigate is the behavior of tugs around intersections.

3.3. ASSET Simulator

To collect statistics related to the performance metrics listed earlier, we are utilizing a fast time Python-based simulator called ASSET (Airport Surface Simulator and Evaluation Tool). ASSET is based on the SARDA framework for scheduling, but with reduced capabilities that allows for rapid prototyping of route planning and scheduling algorithms.

ASSET contains three components: a scheduler, a simulator, and visualizer and analysis tools. The inputs to the simulator include a graphical model of an airport; a model of aircraft (including wing span, length and average taxi speed); and a scenario, a list of departure and arrivals for different aircraft, and the times at which they enter the surface system. The simulator, in conjunction with the scheduler, outputs the surface track information (i.e. the flow of traffic) over time. The simulator also models the 'intent' of the towing vehicles by automatically enforcing the separation constraints and other rules governing safe surface traverse. The ASSET visualizer reads simulator output and displays the progress of the scenario on the airport surface. The evaluation tool reads the simulator output into an SQL database, from which statistical inferences can be made and plotted.

3.3.1. Fast Time Scenario Design

We use the distinctions discussed in (Harvey, et.al., 2003) to define a set of experiments testing the exploration objective: *What if Dallas Fort Worth (DFW) airport has an autonomous tug-based taxi system?* The metrics evaluated in the simulation included the environmental and economic impact of engines-off autonomous taxiing. The baseline we used was no tugs (current practices), and the baseline was compared to the introduction of tugs using real data from DFW surface operations. Some of the assumptions and limitations we identified for these experiments include: the limitation of scenarios to nominal ones only, i.e., ones in which communication, control and execution of plans were perfect. The purpose of the simulation was to form principles, eliminate poor design choices, and refining the concept of operations. We also limited operations to departures only; arrival aircraft were not serviced by tugs. Finally, we assume that all tugs have the same size and capabilities, so that any given tug could be deployed to service a given aircraft.

In the data set we used a single day of operations, with 33 departures and 15 arrivals. We focused on the North Terminal area of DFW, and chose two central tug depots, located in an area of DFW that is currently used as a storage area for surface vehicles. The locations are strategically located to access the departing gates in the terminal. In addition, there is a third tug depot located near the north runway. The assumption here is that after tugs detach at the runway, they should be directly dispatchable to service new aircraft, rather than to automatically return to the central depot. We used the greedy tug dispatching algorithm described above to assign tugs to aircraft. We also ran simulations using varying fleet sizes, from no tugs (baseline) to 34 tugs (therefore, one for each arriving aircraft).

3.3.2. Experimental Results

The ASSET simulator allows for the generation of statistics about the efficiency of different scheduling approaches to taxi operations. Figures 6 and 7 show the results of running the simulator 50 times on test data with respect to two important metrics: throughput and taxi time. In both the figures, the X axis represents tug fleet size, from “No_tugs” to “tug_x”, where x is the tug fleet size. In the Figure 6, the Y axis represents the average latest takeoff time for a departing aircraft. The interest here is to study the effect of adding tug dispatching time to surface operations. More specifically, the interest is to determine a fleet size that is large enough to respond in a timely manner to aircraft waiting to be serviced, but is not so large that the added surface traffic that tugs provide does not slow down operations. The data in the figure suggest that a tug fleet size that is roughly 1/3 of the number of aircraft to be serviced (12) results in a throughput that is close to that which results from having no tugs, thus minimizing the overhead of dispatching.

Figure 7 plots average, low and high taxi times for each tug fleet size, where taxi time is the duration between the start of pushback and entry into runway (which the exit point of the aircraft from the simulator). The data suggest that large fleets of tugs (34) congest the surface movement and hence increase taxi times. But with smaller fleets the taxi time is reduced, and even shows improvements over no tugs. It should be stressed that this improvement is based on rather strong assumptions about the efficiency of tug autonomy (both in improvements in navigation and communication) versus pilot-controlled taxiing with voice communications between pilot and ramp controller. Nonetheless, as the graph also shows, if taxi times can at least compete with engines-on taxiing, then the savings in fuel and emissions with engines-off taxiing demonstrates a clear advantage for autonomy.

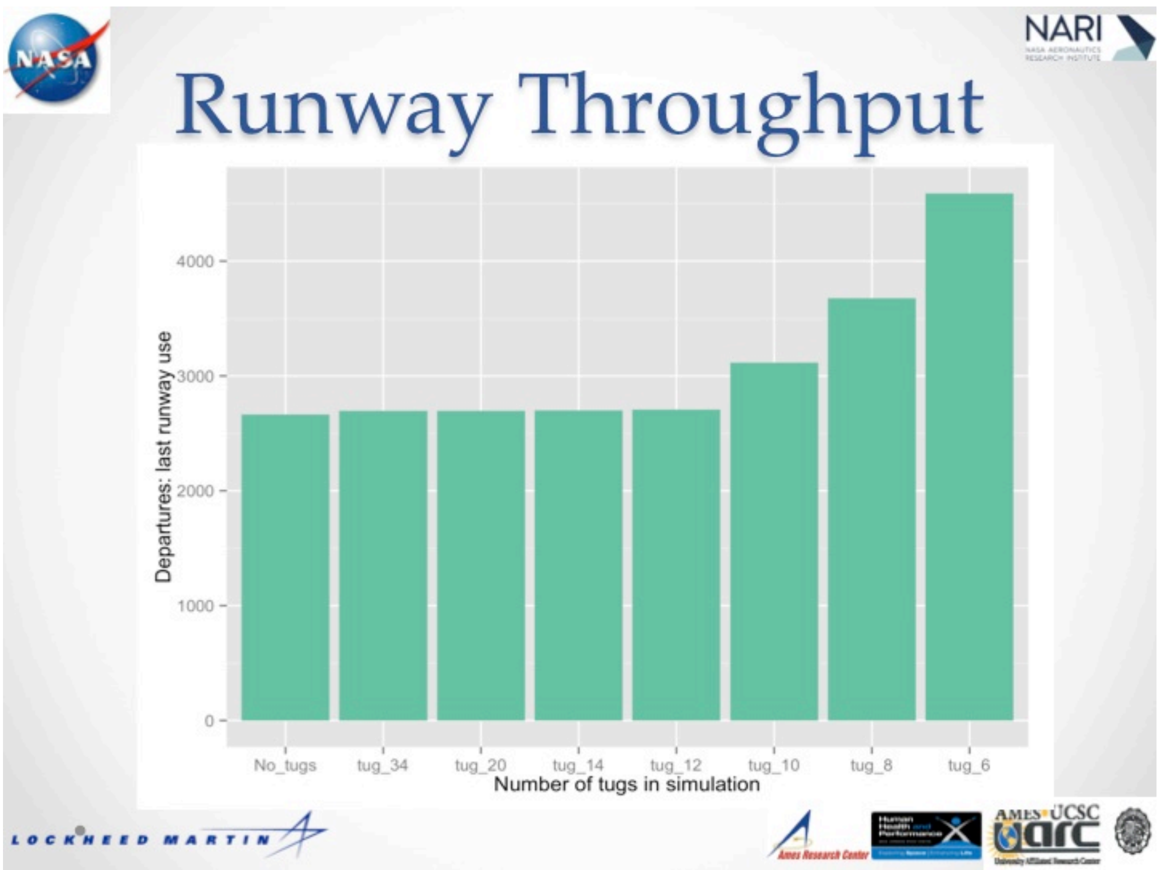


Figure 6 Simluated Results Measuring Runway Throughput for Different Tug Fleet Sizes.

3.3.3. Final Autonomy Score Card

To conclude this section, we summarize the advantages and disadvantages of engines-off autonomous taxiing using self-driving towing vehicles with respect to the performance metrics defined at the outset of this report.

First, with respect to the criterion of safety, autonomous tugs possess dedicated high-resolution sensing and navigation capabilities. By contrast, pilot-crew taxiing is sometimes conducted in parallel with other activities such as safety checks. Second, assuming manual override capabilities, auto-taxiing can be viewed as possessing a 'new set of eyes' to aid in the maintenance of safe operations. The potential downside of autonomous tugs is the need for humans and machines to predict behavior in an environment where humans and machines are operating together.

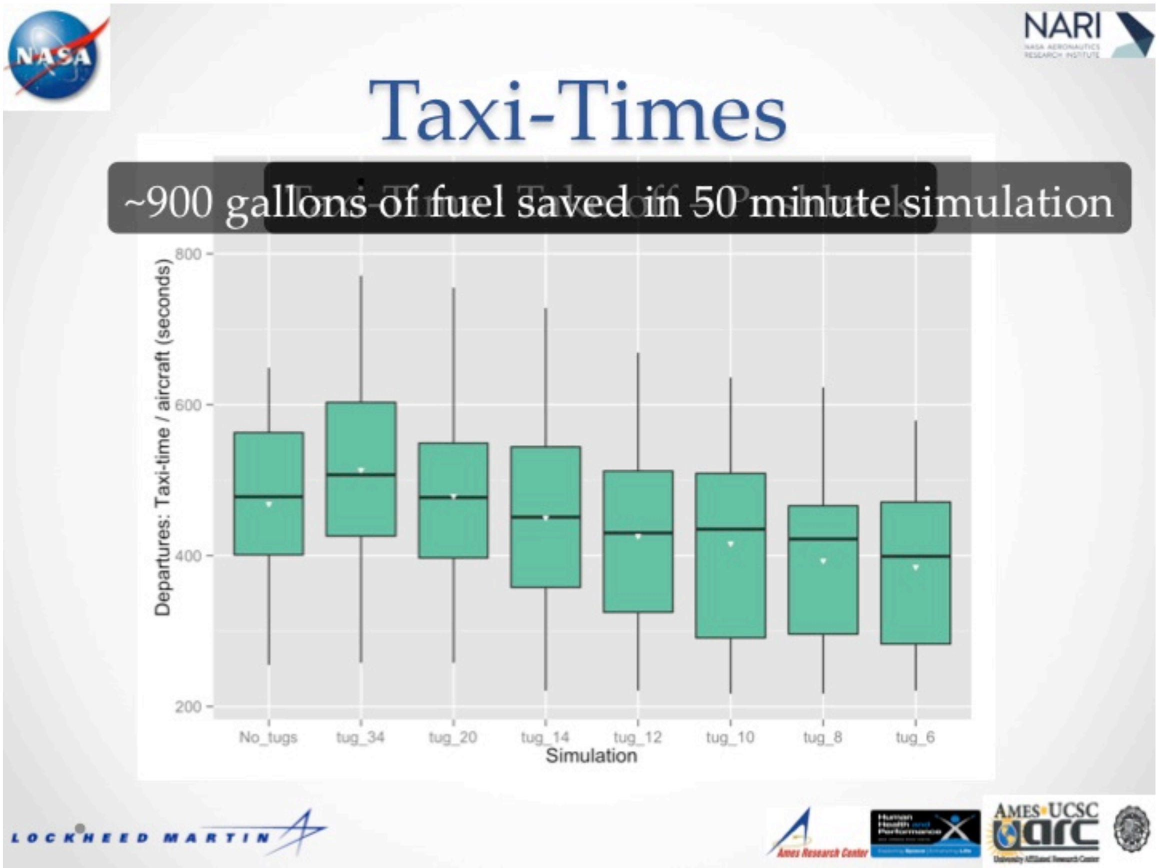


Figure 7 Simulated Average Taxi Times for Different Tug Fleet Sizes.

Second, with respect to human (pilot, ground crew, ramp controller) workload, planning and scheduling routes and releases are automated using SARDA, and the instructions are executed autonomously, thus relieving human operators of these duties. On the other hand, logistics is potentially made complicated, at least initially, because of the need for changes in procedures that result from adding autonomy.

Third, considering the criterion of efficiency, as notes earlier, the use of digital data link rather than voice communication allows for more precision, and the use of autonomy allows for potential improvements in navigation. On the downside, towing vehicles require the overhead of attachment detachment, and dispatching, which make operations more complex and therefore potentially less efficient.

Finally, the environmental and economic impacts are perhaps the most important to the customers of this technology, the airports, airlines, and aircraft manufacturers. In short, autonomous engines-off taxiing inherit the environmental benefits of engines-off taxiing in general, whether manual or not, in addition to the economic benefits arising from reduced fuel use. Arguably, the SafeTug approach requires fewer changes to aircraft design than either TaxiBot or ElectricTaxi, as defined earlier. TaxiBot requires changes to the aircraft to enable pilot remote control of the towing vehicle, whereas ElectricTaxi requires additional weight and power requirements as a result of the auxiliary engine attached to the landing gear. SafeTug is most like what we have been calling 'operational towing' (human-driven separate towing vehicle) with the autonomy replacing the human driver.

The downside economically to SafeTug is the changes to the airport infrastructure and procedures that are required to integrate auto-towing. Some of the changes include: adding to the fleet of ground vehicles at commercial airports; this is an initial cost that the customer (airlines or airports) must absorb, and they must be convinced of a reasonably quick return on this investment. Additionally, it is possible that artificial landmarks might be needed to aid tug navigation, especially to assist in localization if GPS or maps are not available. Third, a wireless communication network must be in place to enable digital data transfer between tower and tug.

Figure 8. Final Tug Autonomy Score Card on 4 Performance Metrics

Fourth, a system of tug depots and charging stations must be in place. Finally, an additional workforce will likely be needed dedicated to supervising tug monitoring, although as we have argued, we envision that much of the monitoring and decision-making can be automated.

4. HMI

The goals of the Human-Machine Interface (HMI) effort were to explore the challenges associated with integrating human characteristics into the SAFETug environment with the goal of optimizing the performance between the human operators and autonomous tugs. For this seedling, the scope of this effort was limited to exploring challenges associated with designing an HMI that can assist ATC Ground Controllers, Ramp Controllers and Pilots in (a) monitoring multiple tugs as they progress throughout the Airport Operations Area (AOA); (b) provide additional information to the tug's route planner to optimize performance; (c) confirm or alter all tug routes and (d) directly intercede when performance constraints have been violated and failure (e.g., a runway incursion) is imminent. For SAFETug operators to successfully perform these tasks, the HMI needs to address the following challenges:

1. Trust calibration i.e. assist controllers and pilots in knowing when to appropriately rely on the automation. Trust calibration is essential for safe and efficient teamwork between human operators and the automated tugs. Under-trusting can lead to suboptimal performance within the SAFETug, Controller/Pilot team dynamic, and can lead to cognitive overload and decreased SA resulting in human error. Whereas, over-trusting can lead to ATC controllers over-relying on SAFETug and not being able to appropriately intervene. In addition to having the right level of trust in a given air terminal condition, the operators also need to have appropriate situational awareness.
2. Maintain Situational Awareness (SA) of the tugs attached and detached from aircraft within the AOA. The tugs will not have drivers in them, as such ATC/Ramp controllers and pilots will need to continuously maintain SA of the tugs as they are performing their tasks within the AOA. SA will also be necessary for assisting the overall performance of the SAFETug system, by providing real-time information of the environment that may be unavailable to the system during route planning.
3. Reduce Workload of the controllers and pilots is essential for successful performance of SAFETug. The goal of SAFETug is to improve throughput at airports which can lead to increased workload due to the increase in vehicle (aircraft and tugs) traffic.

The team addressed the aforementioned challenges by applying an Ecological Interface Design (EID) (Vicente & Rasmussen, 1992) framework in conjunction with a task-based approach to provide calibrated trust, SA and a balanced workload to ATC controllers supervising semi-autonomous tugs. EID is a framework for the design of HMI for complex sociotechnical systems. It uses an Abstraction Hierarchy (AH) which is a type of work domain analysis to determine the constraints and complex relationships of the work environment, making them perceptually evident through the HMI. The EID framework combines the AH with a Skills, Rules and Knowledge (SRK) framework to assist operators in using limited cognitive resources for problem solving and decision making (Vicente, 1999).

The EID method has been shown to be the best framework for the design of HMIs for complex sociotechnical systems (Burns & Hajdukiewicz, 2004; Naikar & Sanderson, 2001; Vicente, 1999). EID is appropriate for this domain due to its focus on making "constraints and complex relationships in the work environment perceptually evident (e.g. visible, audible) to the user" [Gacias, Cegarra, & Lopez, 2010)]. The air terminal environment already contains a number of constraints that must be adhered to, i.e. departure/arrival times, navigation of active runways, aircraft separation, and gate assignments; additional constraints were added for the supervision of the semi-autonomous tugs.

To build and analyzed the initial HMI designed using EID principles the following tasks were accomplished:

- Task 1.0: Understanding the Airport Operations Area
- Task 1.1: Ecological Interface Design: The Abstract Hierarchy
- Task 1.2: Hierarchical Task Analysis of Air Traffic Control and Ramp Tower Operations
- Task 1.3: Human Machine Interface Concept Design
- Task 1.4 HMI Development and Evaluation

4.1. Understanding Airport Operations Area (AOA)

The first task was to understand the environment the tugs will operate in and how the interaction occurs between primary stakeholders (ATC, Ramp, Pilot and Ground). During the initial phases of this effort, the team visited the ATC Towers at Hobby airport (HOU) and George Bush Intercontinental airport (IAH). The team also visited with United Ramp operations at IAH and Southwest Ground operations at HOU. Finally, the team interviewed a current commercial airline pilot. These visits and interview were chosen because these groups cover the majority of the operations that occur in the AOA and as such would have the most interaction with the autonomous tugs, i.e., ATC will need to manage the tugs as they operate on the runways and taxiways; ramp control will supervise the tugs in the ramp area; ground crews will have to work in close proximity with the autonomous tugs and the pilots will need to maintain continuous SA of the tug that is towing them.

4.2. Air Traffic Control Environment

In this section we discuss the information learned from visits with ATC Towers at Hobby Airport (HOU) and Bush Intercontinental (IAH) along with the Ramp control tower at IAH. ATC and Ramp control towers are responsible for the vehicles operating in the AOA. The AOA is any paved or unpaved area of the airport whose intended uses is for the landing, takeoff, or surface maneuvering of aircraft. The AOA can be further divided into movement and non-movement areas. The movement area of the airport consists of the runways, taxiways and other areas used for taxiing, takeoff and landing of aircraft. The non-movement area is all other surface areas within the AOA e.g. loading ramps and aircraft parking areas. ATC manages all aircraft, vehicles, and pedestrians operating in the movement area. At large airports such as IAH, movement within the non-movement area is controlled by a ground or ramp control tower. At smaller airports such as Hobby, there may not be ramp control, therefore as a courtesy, ATC will also manage movement in the non-movement area. The fact that there are two stakeholders for the AOA is critical for the development of the SAFETug HMI. Specifically, requirements for the HMI need to meet the goals of both groups.

During the SAFETug's team site visits, it was noted that high levels of SA and coordination are necessary for managing aircraft in the AOA. Based on discussions with the controllers, the primary method of maintaining SA is through visually watching the aircraft and radio communication. Additionally, SA and coordination is accomplished through the use of flight progress strips. Flight progress strips play a pivotal role in the air traffic controllers' ability to predict the future locations of aircraft. The flight progress strip provides information such as instructions that were issued to the aircraft, and the ability to provide annotated notes. The flight progress strips placement also provide critical information such as ordering of aircraft for takeoff and approach, location, priority etc. Although visual scanning of the environment and flight strips provided the majority of controllers SA, there are a number of technological tools available, such as the FAA STARS and Airport Surveillance Radar (ASR). However, the Airport Surface Detection System Equipment Model X (ASDE-X) is the primary tool used by ATC for tracking aircraft moving in the movement and non-movement areas. Based on our discussions, its utilization varies. For example, discussion with one air traffic controller at HOU highlighted a strong preference for using visual and flight progress strips and very little interaction with the ASDE-X system whereas controllers at IAH readily used ASDE-X to assist in building SA. When the team visited with the ramp control tower at IAH, it was noted that they were more reliant on technology and used systems such as United's GateView system and cameras to provide additional information of the non-movement area of the AOA, see **Error! Reference source not found.**.

*Figure **9**. The various systems used by ramp controllers at Bush Intercontinental Airport. Note that ramp controllers have access to cameras, which are not available to IAH ATC tower*

ATC and Ramp Control require high levels of SA to provide taxiing instruction, gate changes and other instructions to aircraft operating throughout the AOA. During the site visits with ATC and ramp control, the team discussed with the controllers what information is necessary to provide navigation instructions to the flight crews. The controllers noted that the following information is used when determining route for departures and arrivals:

- Safest route
- Runway availability which is based on current flow (i.e. direction of departing and arriving aircraft)

- Type of plane
- Weather
- Pilot experience
- Runway/taxiway closures

The team also discussed with the controllers their biggest challenge to performing their role. The controllers interviewed noted that managing uncertainty is one of their key challenges. Uncertainty can manifest itself in many ways. For example, pushback operations add a level of uncertainty. The pilot radios in a request for push-back, however once given, the controllers do not know if the pilot is going to pushback immediately or a minute later. Another example of uncertainty is in taxiing. Taxiing speeds are not specified and are therefore controlled by the airlines and pilots. This uncertainty can have an effect on ATC ability to predict an aircraft's future location. This is often manifested when working with younger less experienced pilots as noted by one controller; their behavior is less predictable causing greater uncertainty in taxiing instructions. The ATC controllers expressed interest in the ability of SAFETug to remove some of these uncertainties from the AOA. For example, SAFETug would help to remove many of the taxing uncertainties by setting the speed for all aircraft thus making their actions more predictable than current approach.

The team's visits to ATC and ramp control generated a large volume of information which has been captured in Appendix A: Site Visit & Pilot Notes. The following summarizes the takeaways from these visits and how they affected the overall approach of the SAFETug HMI.

- There are two areas of operations for the tugs, the movement and non-movement areas. The movement area is managed by ATC Ground and the non-movement area is managed by ramp control. This will require the HMI to be capable of switching between the groups. Due to the roles and agenda of the two groups being similar, this initial seedling effort focused on designing a single HMI that can be used by both ATC and ramp control.
- Technological tools are not the primary systems used for managing the AOA. Therefore, the SAFETug HMI will need to be designed as a tertiary system, i.e., it will be capable of providing all the necessary features for managing the AOA but will not be the primary approach.
- To maximize adoption, the SAFETug HMI should fit within the existing flow of operations. There are a large number of technological tools currently employed by controllers that manage the AOA. Creation of another HMI just for SAFETug would not be beneficial, therefore an alternative approach is to extend the existing ASDE-X system with the additional features necessary to manage not only aircraft but also autonomous tugs.
- Controllers use information from a variety of sources when determining pushback and taxiing instructions. Therefore, it will be necessary for the team to determine the information producer's necessary for the SAFETug system to generate safe and efficient routing information.
- The biggest challenge for controllers is managing uncertainty. Reduction of uncertainty should be a primary goal of the SAFETug HMI.

4.2.1. Ground Operations

In addition to visits with ATC and Ramp towers, the team also visited Southwest Airlines ground operations at Hobby Airport. Ground operations maintain the gates and associated vehicles such as tugs that service the gates. This visit was done to provide a greater understanding of the environment and personnel that will be working and interacting with the autonomous tugs. This information is critical to the development of an HMI that can assist the tugs when navigating in the terminal area interacting with ground crews.

Within the ramp area, there are a number of personnel and vehicles involved with managing arrival and departure aircraft. Each gate at an airport has a designated set of equipment which includes the pushback tug. The equipment is owned by the airlines and is not shared between airlines. The pushback tugs can either be diesel or electric and are classified as towbar or towbarless. Towbarless tugs do not use a towbar and instead they scoop up the nose wheel of the aircraft, providing greater stability and control. The attachment of a towbarless pushback tug to an aircraft takes approximately 5 minutes. The focus of the SAFETug system is on towbarless pushback tugs thus when autonomous tugs are mentioned, it is in reference to towbarless pushback tugs. The overall turnaround time, i.e., the amount of time for an aircraft to arrive and depart is 35-40 minutes (this is unique to Southwest, other airlines take longer).

Each gate has a primary ground crew. They receive their gate assignment when their shift begins and they work that gate for the entire day. If there is no aircraft at their gate then they have a sister gate that they can assist. Each ground crew member can work any of the ground crew roles. Communication between within the crew is done via wireless headset.

During pushback, wing walkers use hand signals or wands (for inclement weather) to provide information to the tug driver. Most of the flight crew's interaction is with ATC and ramp control, however the flight crew informs the marshal of when they are ready for pushback. Once pushback begins, the tug driver has control of the aircraft. The flight crew has a hot microphone to the ground crew in case of emergencies. It will be necessary for the autonomous tugs to be able to recognize the ground crew and also understand both verbal and hand signal communications.

There is a safety buffer zone around an aircraft that cannot be violated during the arrival and departure of an aircraft. The area in which ground vehicles operate around the aircraft is fairly limited and thus can restrict the movement of large vehicles such as pushback tugs. Currently, the marshal and wing walkers make sure that this area is clear. Anti-collision lights inform all ground personnel that the pilot is ready to pushback and that the aircraft will begin moving. While moving, the aircraft has right of way, all other ground vehicles must stop and wait for the aircraft to clear their path.

In addition to understanding the operating environment of the ramp area and the ground crews, the team also investigated their opinion of the SAFETug system. Overall comments from ground personnel was positive with additional suggestion of automating other vehicles such as the baggage carrier. Their only concern was in regards to the ability of the autonomous tugs to navigate in the ramp area due to the dynamic nature of the environment. They suggested having the pushback portion performed by the driver and once the aircraft is away from the gate, the driver could then leave and allow the autonomy to take control.

Appendix A: Site Visit & Pilot Notes, provides detailed information on the teams visit with Southwest Ground Operations at HOU. The following summarizes the takeaways from this visit and how they affected the overall approach of the SAFETug system and HMI.

- Tugs should arrive before the aircraft. There may not be enough room to maneuver the tug once the aircraft arrives at the gate.
- The tug needs to be able to communicate with the pilot at all times and vice versa. This will be accomplished through a pilot HMI designed specifically to work with a pilot's digital display. This will provide the pilot with information on the tugs' readiness for pushback, allow the pilot to inform the tug to begin pushback, and also emergency controls.
- Marshals should initiate autonomous pushback once the area around the aircraft has been cleared. Once the pilot informs the tug that they are ready for pushback, it will be the marshal who confirms the start of the pushback. This adds an additional safety check to make sure the area is clear. Although out of the scope of this effort, it is envisioned that the Marshal will use hand signals to signal to the tug the all clear to begin pushback.
- Wing Walkers will still be used during pushback to inform other vehicles of the aircraft movements, therefore the autonomous tugs must account for the wing walkers that will be within the aircraft's safety buffer.
- The autonomous tugs will have to recognize the hand signals from the wing walkers.
- Allow the autonomous tugs to be drivable by ground crews. This will allow the airlines to determine how to use the tugs in the ramp environment.

4.2.2. Pilot Interviews

The team also had the opportunity to interview a commercial pilot. The pilot provided his perspective on what information they need for safe towing of their aircraft. The notes from the interviews is located in Appendix A: Site Visit & Pilot Notes. Below are a few of the highlights that had an effect on the SAFETug design.

Based on the interviews, the following was determined:

- Autonomously towing arrival aircraft will only be necessary if the gate is unavailable. Based on comments from the pilot; if he does not have to stop his aircraft than fuel consumption on arrival is minimal. If pilots cannot taxi right to the gate and have to wait in a holding area, then autonomous tugs could be used to tow the aircraft from the holding area to the gate. The pilot noted that when stopped in a holding area, they usually shutdown the engines and have to re-spool the engines to get the aircraft moving again to the gate. Re-spooling of the engines is costly and thus they recommended that tugs be used for towing of arrival aircraft only when the aircraft cannot taxi directly to its gate.
- Tugs used only for taxiing out would still be a tremendous saving. As such, for this effort the focus of the SAFETug HMI is on departure scenarios.
- Majority of the safety checks can be performed while being towed, this includes spooling of the engines. The only safety check that cannot be performed during towing is of the nose wheel due to it being locked in place by the tug. This in theory can allow the tugs to tow aircraft to the hold short line.

- Everything is going on tablets so a SAFETug Pilot display could be integrated into the crew cockpit tablet.
- Pilot needs to know what the tug is currently doing and what the tug is planning to do.
- Any cockpit crewmember should have the ability to stop the tug in an emergency. This should be done using the brakes.
- Tugs returning after towing an aircraft may have a difficult time finding a route back to the terminal/tug depot.
- Taxiing at some airports can be a challenging due to layout and taxiing designations.
- Tugs should disconnect from aircraft at the hold short line. This will give the crew an opportunity to start engines.
- Tugs need to be able to inform pilots of when it is clear of the aircraft after detaching so that the pilot can proceed.

4.2.3. Summary

All the information gathered from the site visits and pilot interviews were consolidated in a mind map that shows the flow of communication including the technologies used between the various stakeholders (see Appendix B). Based on the site visits and pilot interviews, the team decided to focus on designing the prototype SAFETug HMIs for the ATC/Ramp controllers and flight crews. The SAFETug system will have the greatest impact on these two groups' roles and responsibilities. Additionally, it will be these groups that have the most interaction with the SAFETug system. Designing the HMI for these two groups will provide the maximum understanding of how SAFETug can be used. An HMI is not designed for the ground crew at this time. However, future research will explore how ground crews should interact with SAFETug. Preliminary discussions have focused on speech and gestures as the primary form of interaction with the autonomous tugs by the ground crew.

4.3. Ecological Interface Design: The Abstract Hierarchy

The site visits and interviews provided an understanding of the operating environment which is essential for developing the SAFETug HMI using an Ecological Interface Design (EID) approach. As previously mentioned, EID is a framework for the design of HMIs for complex sociotechnical systems

One of the major issues with designing an interface for a complex system such as the AOA is that it cannot be described in terms of a set of nominal tasks or procedures (Meister, 1996; Rasmussen et al., 1994; Vincente, 1999). In systems with a high level of automation, the user must deal with novel and unexpected contingencies (Vicente 1999). Therefore, an Abstract Hierarchy (AH) is used to define the work domain of the ATC and Ramp Control. This information is then used as the basis for the ATC/Ramp control HMI design

An AH typically describes (a) the functional purposes of the work domain; (b) the abstract functions describing the priorities that must be achieved to carry out the work of the system; (c) the general functions or causal laws that must be executed and coordinated to achieve work domain objectives; (d) the physical functions, such as those afforded by the physical devices of the work domain; and (e) the physical form, such as the physical devices themselves (see **Error! Reference source not found.** for an example AH). The links between the layers of an abstraction hierarchy express means-ends or how-why relations. By using an abstraction hierarchy to help design the system, the physical-device solutions of a proposed design (physical form and physical function) can be evaluated in terms of how well they fulfill the higher-level functions and objectives of a work domain (purpose-related functions, priorities and values, functional purposes). Note that an AH differs from task analysis. The AH focus is on how the operating domain works regardless of task, whereas task analysis focus is on understanding a sequence of steps to be accomplished. A task is an operation that people do, while a AH focuses on the purpose is of the system. Tasks will change, while purposes stay constant. This minor detail is important, in that by understanding the purpose of the system it is then possible to define the constraints necessary for fulfilling that purpose. This then allows for designing a system that focuses on recognizing when constraints are violated which is independent of the task.

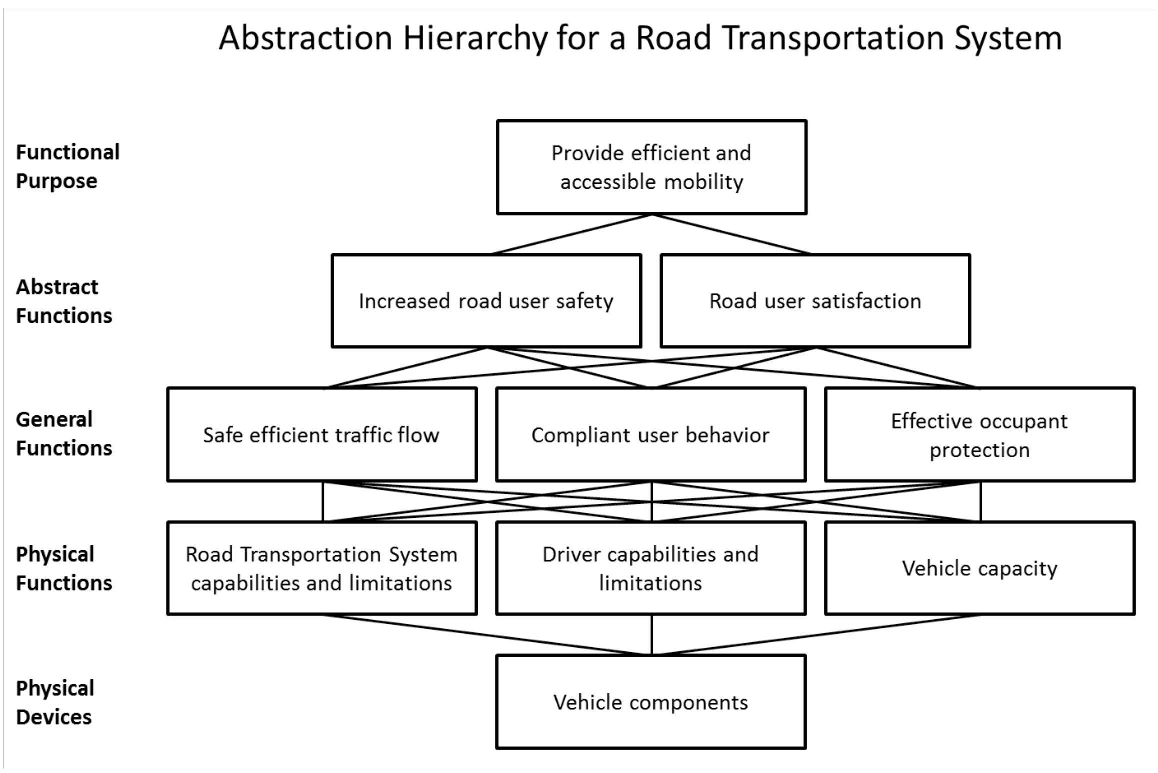


Figure 10: Example of an abstraction hierarchy for a road transportation system. Adapted from: Salmon et al. (2007). Work domain analysis and intelligent transportation systems: Implications for vehicle design.

Using the information gained from Understanding Airport Operations Area (AOA) an AH was done for the SAFETug system, see Appendix C for the completed SAFETug AH. Beginning at the top level (**Error! Reference source not found.**), the Functional Purpose describes what the SAFETug system is designed to do, which is provide the user with enough information to maintain high situational awareness of the entire system in order to facilitate movement of airport traffic efficiently and safely. Situational awareness of the system includes, for example, movement of all airport traffic in terms of outgoing/incoming aircraft, tug locations, knowledge of current and future traffic flow, and system state. As shown in **Error! Reference source not found.**, the SAFETug functional purpose is broken up into two distinct categories for the work domain – safety and efficiency.

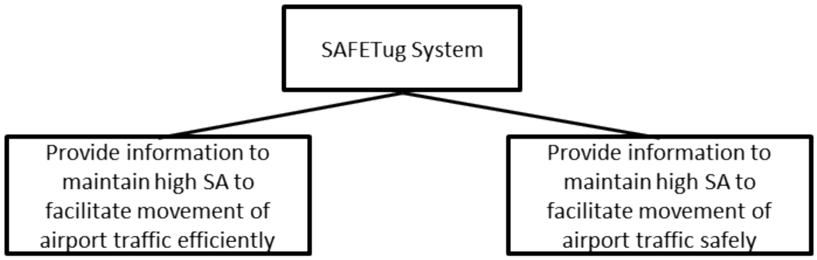


Figure 11: Functional Purpose of the SAFETug system

The Functional Purpose includes evaluation criteria to help the operator determine if the constraints applied on the work domain have been violated. For the SAFETug system, we can identify the following criteria:

- The tug must succeed in transporting a departing aircraft from the gate to a disconnection point.
- The tug must succeed in navigating back to the gate or the tug depot
- The transportation needs to be efficient and safe.

The Abstract Function level is a description of the causal relationships underlying the work domain. These are priorities that must be achieved for the system to function and cannot be altered. In simple terms, we ask the question "What information must flow through the system in order to support the Functional Purpose domain?" As ascribed at the Functional level, SAFETug operators must have good situational awareness in order to meet both purposes. Therefore, the operator will need information from a number of different sources in order to gain a global perception of the airport traffic. As shown in **Error! Reference source not found.**, these sources would include: information on aircraft arrivals and departures, tugs pushing aircraft from gate and path to runway, location of other aircraft, if traffic is heavy then location of hold positions for the aircraft, tug routes to and from aircraft or gate, and any off-nominal information such as an emergency. It is these pieces that flow together to support the Functional Purpose of the system to provide high situational awareness.

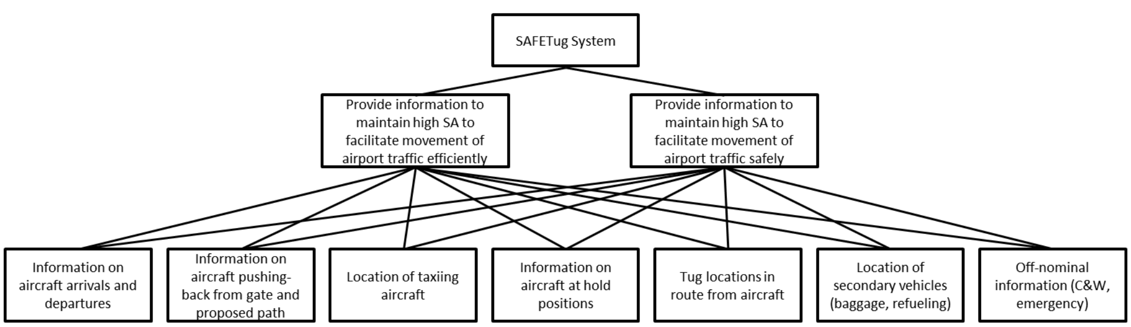


Figure 12: The Abstract Function of the SAFETug system.

Generalized Functions explains "how" each level of the Abstract Function are achieved. For example, to generate the Generalized Function for "How is information on aircraft arrivals and departures gathered?", a number of sources are available to generate this information (see **Error! Reference source not found.**) – surveillance radar would provide incoming flight information, the Flight Data Processing System would give take-off and flight plan information, an arrival and departure manager could be implemented at the airport, the flight progress strip would contain both arrival and departure times as well as gate information, and the ATC operator, the flight crew, or ramp controller would all control arrival and push-back information that would be communicated. It should be noted that not all these sources are available at all airports and some are only prototype technologies.

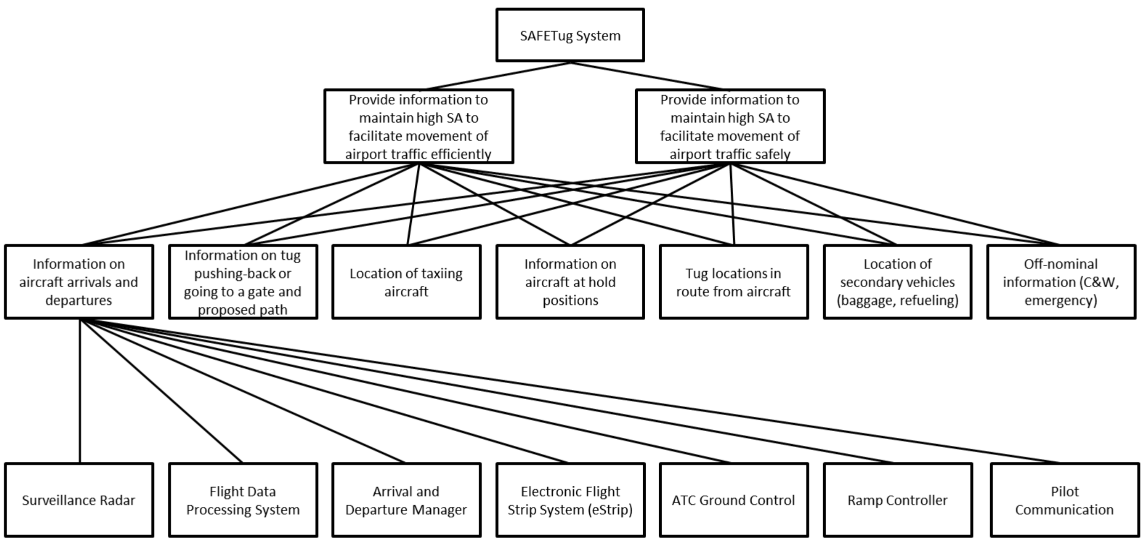


Figure 13: A partial Generalized Function for the SAFETug system.

The Physical Function layer represents the various components that make up the work domain and their limitations and capabilities. In context of the SAFETug system, these physical components would include, tug sensors, cameras, displays, automation software, battery life of the tug, surface radar, or terminal automation system. It can also include human elements such as cognitive (e.g., overload of information) and physiological (e.g., cannot see) limitations. There may also be environmental limitations, for example, weather (e.g., visibility) and physical (e.g., cannot see around a building) limitations. It is these constituent parts that are the foundation of the system without these components the system cannot operate. Given this is the initial seedling effort of this project, not all these components are known. Therefore, we have placed a single box to represent this level. The final level is the Physical Form of the system, which includes a description of the parts that make up each of the Physical Functions (e.g., wires, batteries, wheels, etc.). Since this list would be rather extensive, it is omitted from the current report.

4.3.1. Task Analysis of Air Traffic Control and Ramp Tower Operations

A Hierarchical Task Analysis (HTA) for a nominal departure was also completed as part of this effort, see Appendix D. An HTA is a method for understanding the high level tasks to be accomplished and decomposing them into various subtasks. Using an HTA approach, the team is able to capture the key elements of the departure task necessary for pushback and taxiing, which in turn allows the team to determine which tasks need to be accomplished by SAFETug.

The HTA also helps to validate the WDA i.e. if all the features of the system are correctly provided through the WDA, then the task should map a path in the hierarchy. For the HTA, we focused on a nominal scenario of moving the aircraft from gate to runway using an autonomous tug. The HTA was completed using the information acquired from the site visits, pilot interviews and also literature reviews.

To perform this scenario, the system would consist of the SAFETug system (Automated Planner, Tug Autonomy, and HMI controller), Cockpit crew, ATC Tower, Ramp Control and the Air Marshall. Below we reference the high level tasks that must be accomplished during a nominal pushback and taxiing scenario.

The SAFETug planner assigns a tug to service gate. The tug departs from the depot and arrives prior to the aircraft. The aircraft arrives and the tug waits until the Marshall signals that it is safe to attach. Attaching the tug early to the aircraft allows the flight crew an opportunity to inspect the attachment when they are performing their safety checks. The SAFETug planner suggests taxiing instructions to the HMI ATC/Ramp controller for review. Once the HMI controller approves the route, it is then displayed to the flight crew HMI. The pilot verbally confirms the route with ATC and uses the tablet to confirm the route with the SAFETug system. The SAFETug system sends the route to the autonomous tug. The pilot request permission to pushback from ATC or Ramp control. Once approved, the tug begins the pushback sequence and tows the aircraft to the runway. At the hold-short line or some alternative detachment point, the tug detaches, signals the all clear to the flight crew and the aircraft continues under its own power to the assigned runway. Appendix D: Hierarchal Task Analysis depicts this nominal departure scenario.

4.3.2. Human Machine Interface Concept Design

As stated previously, SAFETug at its core is a transportation system; its *functional purpose* is to assist ATC/Ramp Control in moving aircraft efficiently and safely through the AOA. Therefore, the interface must present information in a manner that the user can recognize inefficiencies and intervene if necessary. To accomplish this, the underlying system will be required to send, capture, organize, and display information from a number of data and communication sources. This information then needs to be represented in a fashion that supports trust calibration, appropriate SA, and workload through optimal usability. To achieve this, the team focused on the following:

- Build upon already existing systems and layouts. This will allow for transfer of training and match with existing mental model of interface operations.
- Use common interface elements. The tendency when adding to an already existing system is to make new UI elements; we tried to avoid this strategy.
- Keep the layout purposeful.
- Strategically use color. Again, the tendency would be to add color to existing or new UI elements, this could make the interface more confusing and cluttered.
- Use typography to create hierarchy and clarity. Different sizes, fonts, and arrangement of the text help increase *scanability*, legibility and readability.

- Make sure the system communicates current status appropriately and without confusion (contradiction) – salient nominal and emergency states.

For this initial seedling system we focused on the HMI design for the ATC/Ramp Controllers (SAFETug Controller HMI) and Pilots (SAFETug Pilot HMI). These are the two groups that are primarily responsible for the pushback of the tug and its movement from gate to runway. It should be noted that in the SAFETug Concept of Operations, the Ground Marshall will also have limited interaction with the autonomous tugs. The Marshall would be tasked with verifying the area around the aircraft is clear and providing a signal to the tug that it can commence pushback. This signal could take the form of a vocal command, button or hand signal. Due to the operating environment of the ground crew, vocal commands will not be the best option. Additionally, having a button on the tug places the Marshall within the tug's safety barrier and could lead to accidental incidents; therefore the ideal approach for interaction between the autonomous tugs and Marshall is via hand signals. Future work will explore the feasibility of this option.

4.3.2.1. SAFETug HMI Design for ATC/Ramp Controllers

The HMI design for ATC/Ramp controllers is based on the goal of moving aircraft efficiently and safely throughout the AOA. Based on information from the site visits and AH, we focused the HMI design on providing controllers with the ability to perceive, comprehend and project the actions of the autonomous tugs. Additionally, the SAFETug HMI provides controllers with the ability to interact with the system by confirming/modifying routes, and providing additional information unknown to the system such as restricted areas. The SAFETug HMI is also designed to provide emergency tug controls.

The team decided to base the design of the SAFETug HMI on two systems; 1)the Airport Surface Detection Equipment, Model X (ASDE-X), which is an airport surface surveillance system that provides seamless surveillance and aircraft identification to air traffic controllers (see **Error! Reference source not found.**), and 2) the electronic progress strip (e-Strip) system, which plays a central role in air-traffic control by providing several important pieces of information to the controller. As previously mentioned, by extending existing systems, we can better match the existing mental model of interface operations and also decrease the amount of training necessary. For the SAFETug Controller's HMI, these systems would be extended to provide information on the autonomous tugs, e.g., tugs' status, location, and emergency controls. This first year's effort was to create a prototype SAFETug HMI which includes defining the basic functionality.

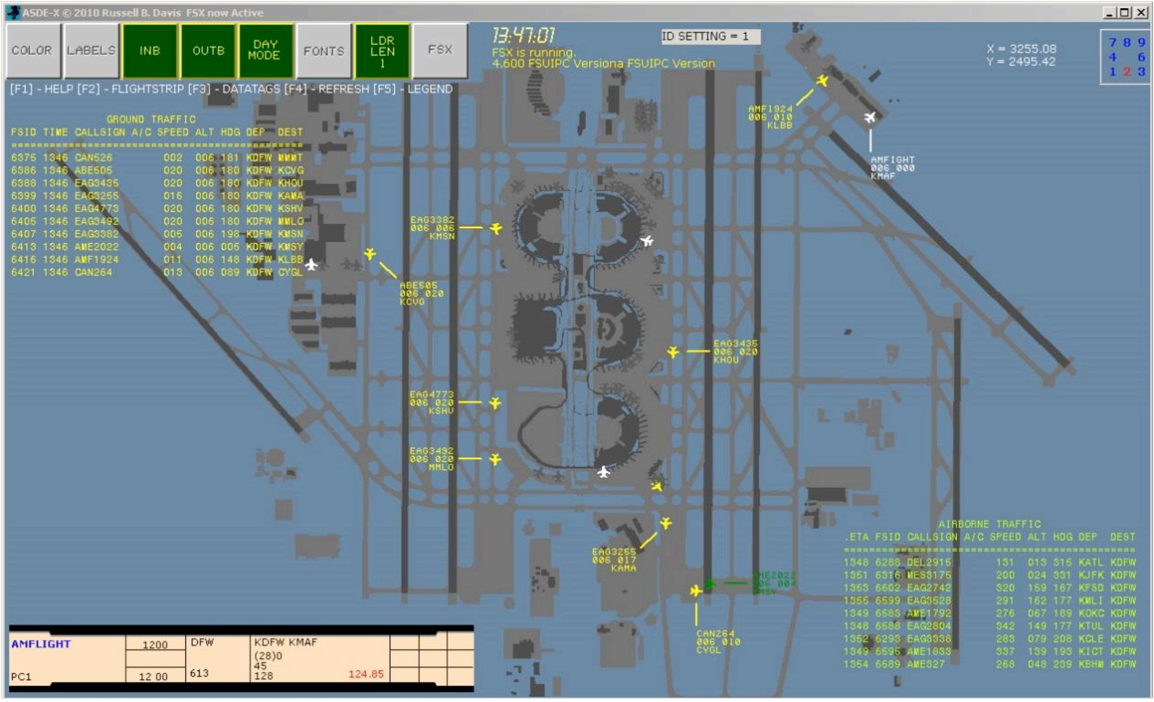


Figure 14: ASDE-X system interface for the Dallas-Fort Worth Airport.

4.3.2.2. SAFETug HMI Design for Pilots

The HMI design of the pilot interface is based on their SA needs and on their ability to understand taxi instructions. This information needs to be readily available so that pilots can follow current FAA guidelines of reading taxiing instruction verbatim back to ATC. Additionally, pilots need the option to adjust a tug's route when necessary. This requires interaction between the Pilot, SAFETug system and ATC. Finally, the pilot also needs access to emergency controls for their attached autonomous tug. The design of the Pilot HMI is grounded on the Airport Diagram and is a trimmed down version SAFETug Controller HMI.

4.3.3. HMI Development and Evaluation

We used the information from site visits, interviews and the EID to develop an initial version of the controllers and pilot HMI. We then evaluated the initial system using usability and domain experts. Their feedback led to improvements of the HMIs. This cycle was repeated twice with usability and domain experts to come up with the final version of the controller and pilot HMI displays. Initial paper mockups were developed and used for each of the evaluations. An interactive HTML prototype of the controller HMI was also developed.

Error! Reference source not found. is the initial design for the SAFETug Controller HMI. This design features an e-strip display, tug display, and extended ASDE-X display system. The goal of the three displays is to integrate multiple surveillance technologies, to provide a greater comprehensive picture of ground operations. Two of the displays (e-strips and ASDE-X) are existing systems which have been extended to manage information from the SAFETug System. The tug display is a new system that is specific to providing detailed information about the autonomous tugs working in the AOA. In the following sections, we will discuss each of the three systems that comprise the SAFETug Controller HMI.

Figure 15: Conceptual design of SAFETug workstation for ATC/Ramp control. Focus is on minimizing changes to current approach by leveraging existing technology.

4.3.3.1. e-Strip Display

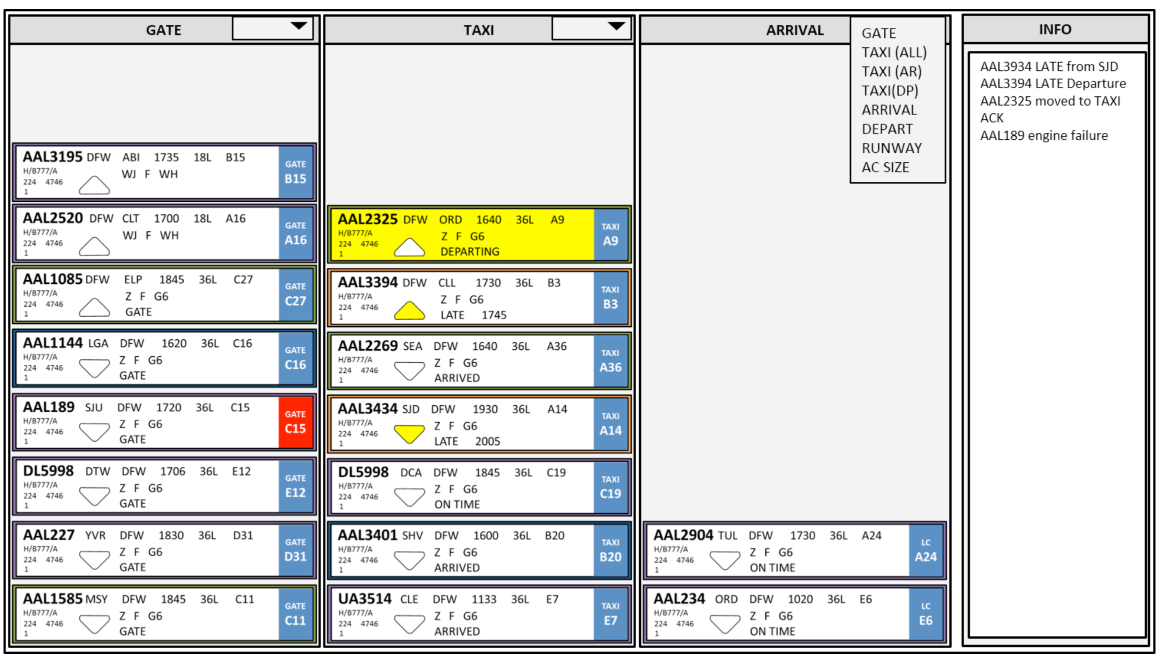


Figure 16: Prototype e-strip display developed for the SAFETug system.

Error! Reference source not found. shows the prototype e-strip display. For this initial effort, the e-strip display has been extended to have four columns of information, one for updated information from the system, and three for the e-strips. The e-Strip display has three columns as gate, taxi and arrival, however, as shown by the drop-down menu, the columns can be sorted in many different configurations such as runway and aircraft size. Each e-strip () has a color strip on the right side which is used to show status (e.g., blue is nominal, red is emergency). Also, around the edge of the e-strip is color to denote aircraft size, see **Error! Reference source not found.**. This is similar to how color is used in current systems such as GateView. When the team discussed the use of colors with flight controllers, many of them said they used the color for quick SA of the size of aircraft at specific gates. They know, for example, that they should only see dark colors at certain gates on the display.

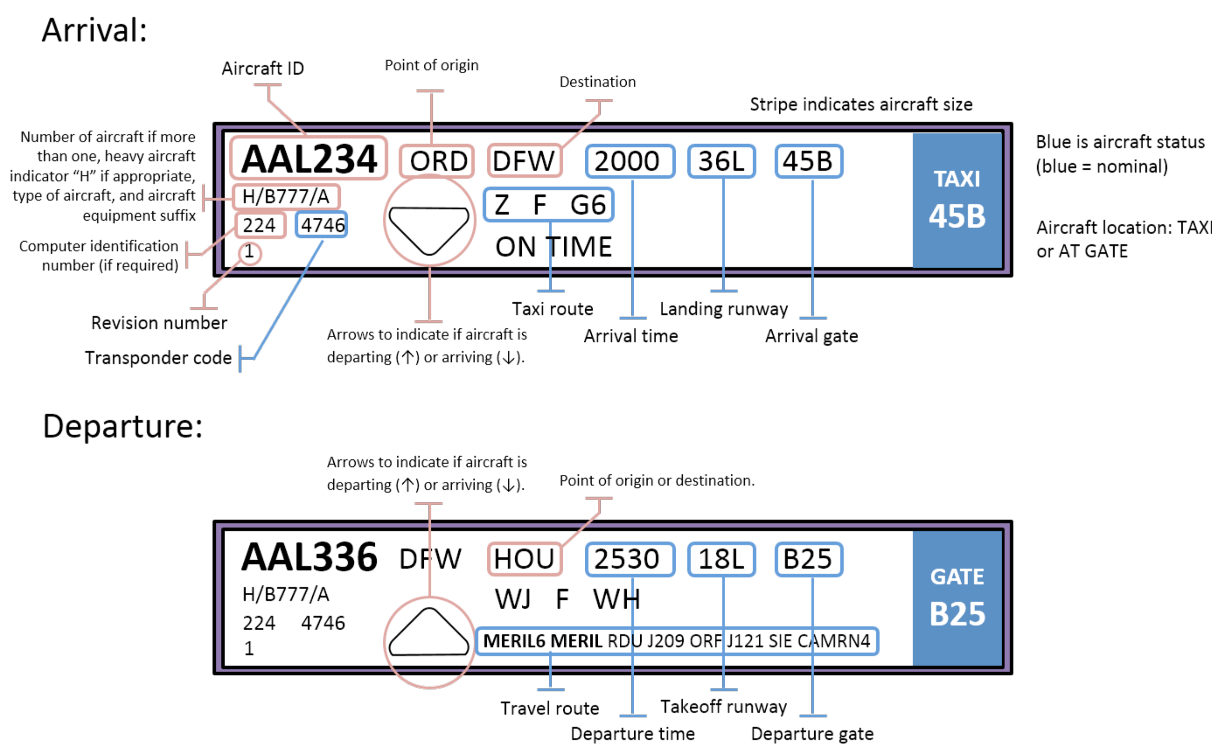


*Figure 17: Baseline proposed e-strips for the SAFETug HMI. Red is **existing** information used with the current flight progress strips, blue is the new information.*

4.3.3.2. Tug Surveillance Display

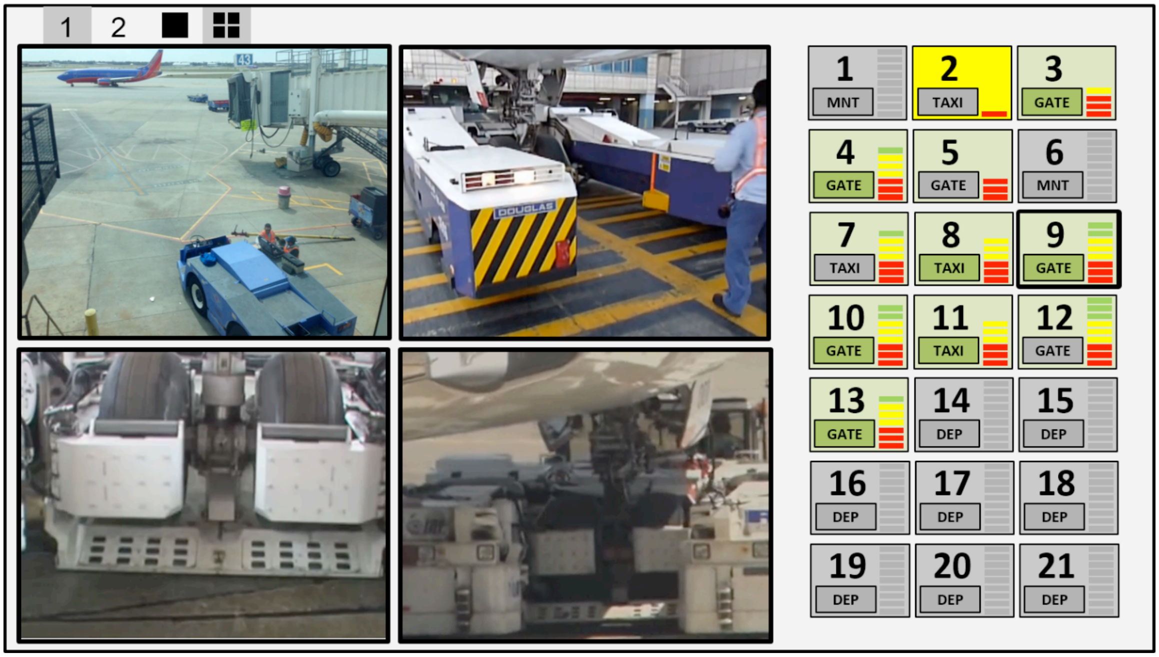


Figure 18: Tug Surveillance Display with the left showing the camera views chosen by the controller and the right showing the tugs status.

The second baseline prototype is the tug surveillance display. As shown in **Error! Reference source not found.**, the display consists of two sections, camera views which the controller can change as necessary and tug status. The tugs are represented by boxes that provide information using text and color. The primary box color denotes status (e.g., gray is not in use, green is in use). Within each box is a small box that gives the location of the tug (e.g., gate, depot) and the color of that box denotes whether the tug is attached to a plane or not (e.g., gray is not attached). Also, within the primary box is a fuel/battery life indicator that uses color for various percentages of life.

4.3.3.3. SAFETug-ASDE-X

The last display for the SAFETug Controller HMI is the SAFETug-ASDE-X system. Shown in **Error! Reference source not found.**, the design for the initial SAFETug-ASDE-X is very similar to the current ASDE-X system already used by controllers. Similarities include color usage for aircraft status (see **Error! Reference source not found.**), aircraft labels and an inbound/outbound traffic table. The buttons at the bottom left, control what information is shown on the display. The *Labels* button shows airport taxi designations. The *INB/GND* button is a 3-way toggle in which, the first push shows the inbound traffic table, a second push displays the ground traffic table and a third push shows both inbound and ground traffic tables. The *Arrival* button is a 2-way toggle, where the first push displays taxiing aircraft and a second push shows aircraft information. The *Depart* button is also a 2-way toggle, where the first push shows taxiing aircraft preparing to depart and a second push shows aircraft information. The last two buttons, Tugs and Routes, display the location of the tugs and their planned routes respectively. Additionally, this initial SAFETug-ASDE-X uses popups to provide the ability for controllers to interact with the SAFETug system. Appendix E: Initial SAFETug ASDE-X Display has the entire mockup design for the SAFETug ASDE-X display.

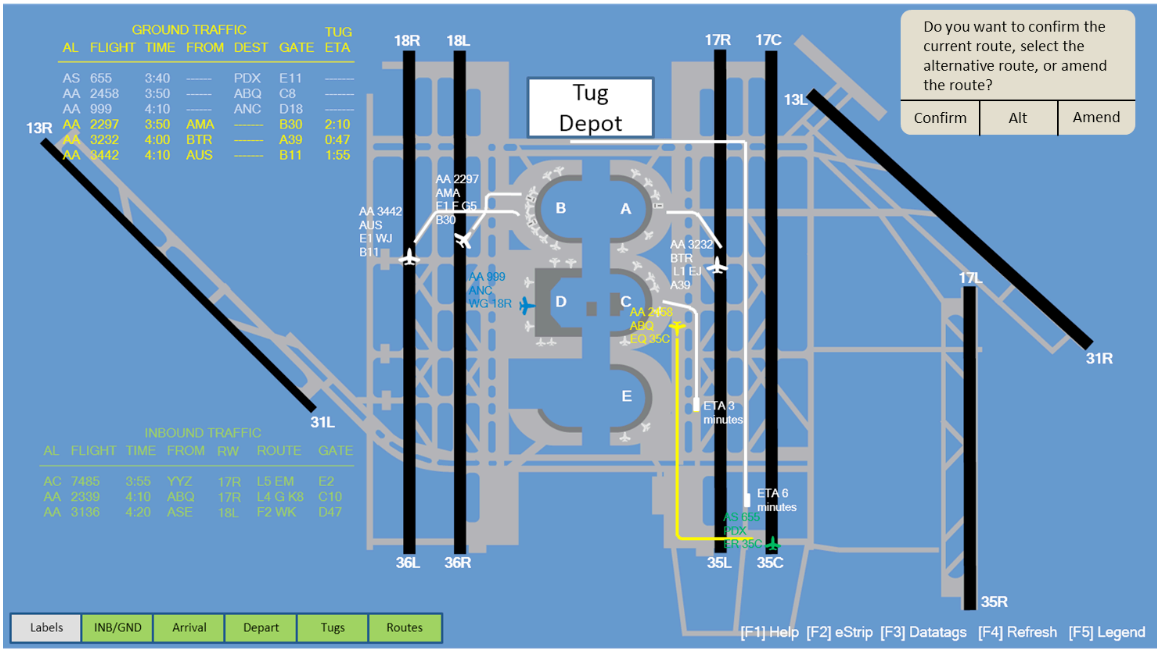


Figure 19: The first prototype SAFETug-ASDE-X display.

Figure 20: First iteration for status color of aircraft and tugs for the SAFETug-ASDE-X system.

4.3.4. PILOT HMI

A paper mockup of the SAFETug Pilot HMI was also developed for evaluation. The pilot display is a minimized version of the SAFETug ASDE-X display. It is designed to fit on a tablet device used by the flight crew team, see **Error! Reference source not found.**. Selecting the SAFETug button will bring up a display similar to the SAFETug ASDE-X display, **Error! Reference source not found.**. **Error! Reference source not found.** shows a sample set of the paper mockup displays for the pushback procedure from the pilot's perspective. Appendix F: Initial Pilot Display Mockup has the entire mockup of the initial Pilot Display.

Figure 21: Sample pilot login display for SAFETug-ASDE-X

Evaluations

A heuristic evaluation (Nielson & Molich, 1990) was performed on the Pilot and SAFETug-ASDE-X display. Due to time and cost constraints, the team decided to focus on evaluating and developing the SAFETug-ASDE-X display as it would serve as the primary tool for interacting with the SAFETug system. Five usability experts and one domain expert reviewed the paper mockups of the Pilot and SAFETug-ASDE-X display. The experts provided feedback on potential usability issues of each of the systems. **Error! Reference source not found.** and **Error! Reference source not found.** lists some of the feedback received and also how the team addressed those concerns, see

Appendix G: Heuristic evaluation of Initial SAFETug-ASDE-X Display for the full heuristic evaluations.

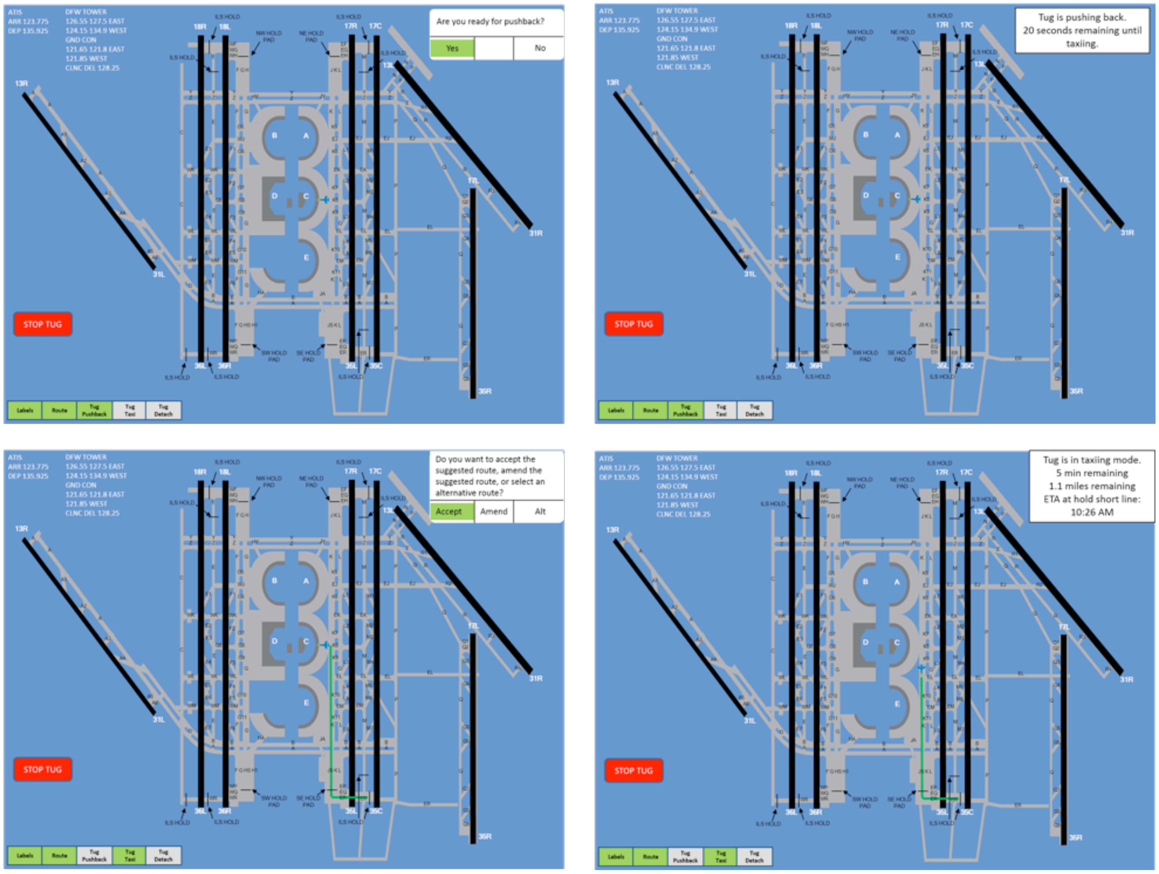


Figure 22: Sample pilot displays for the SAFETug-ASDE-X.

Table 1: Summary of suggestions provided from evaluation of SAFETug ASDE-X display

Comments	**Changes**
Tugs and Routes	
Use two tug depots, one on each end of airport with a road only for tugs to travel to/from depots.	Decided not to be specific about location of a tug depot since this would be different based on the airport.
Symbology and colors difficult to remember for tugs. Hard to see if attached.	Will use only aircraft color to represent tug information and remove added tug icons.
Tug disconnect point needs to be before hold-short line in case of aircraft issue.	A disconnect point was added to the display before the hold-short line and an engine start-up point is given.
Display Information	

INB/GND table format is good, should only show information for aircraft within 15 mins of arrival and only give where plane came from not where it is going.	Went back to a table more similar to the current ASDE-X table. Will only display aircraft within 15 mins of arrival. Providing where plane came from for arriving and where plane is going for departing.
Need to show SID information on table.	This was added back to table.
Need the ability to toggle on/off information.	This ability is provided by the display.
Pilot Display	
Need to have ability to change taxi route.	This was provided in the next iteration of the display.
A suggested outline for the interaction was given for pilot and controller.	This was used in the next iteration of the display.

Table 2: Summary of suggestion provided from evaluation of pilot display

Comments	**Changes**
Numerous wording changes.	These suggestion were integrated.
Do not use distance only time remaining.	This suggestion was integrated.
Show route path information.	This suggestion was integrated.
Provided why for pilot to suggest an amended route.	This suggestion was integrated.
Clearly show the tug detach point.	This suggestion was integrated.
How route status disappear as plane is progressing.	This suggestion was integrated.
Need a way to show status of SAFETug planner.	This will be integrated in a later version.
Change location of buttons and popups.	This suggestion was integrated.
Make sure all information is dynamic, for example countdown.	This suggestion was integrated.
Provide accept button and only show stop button when tug is attached and moving.	This suggestion was integrated.

Based on these evaluations, the initial Pilot and SAFETug ASDE-X displays were updated, see **Error! Reference source not found.**, **Error! Reference source not found.** and **Error! Reference source not found.**. Two of the major differences is the addition of a black information strip at the top of the HMI, where the buttons and quick-look information can be seen better, and the replacement of the information buttons with information 'tabs'. The information tabs can be added or removed from the display and are reconfigurable (i.e., location, size and shape) based on the controller preferences. The prototype display shows four sample tabs: traffic, weather, status, and tugs. Each tab can be minimized when necessary. Also, the plane icon colors were changed slightly and are more in-line with the current ASDE-X display, **Error! Reference source not found.**. As stated, the pilot display is based on the controller display and thus has been modified to match shown in **Error! Reference source not found.**.

Appendix H: SAFETug ASDE-X Display and Pilot Iteration v2 has completed mockups for the modified HMI's.

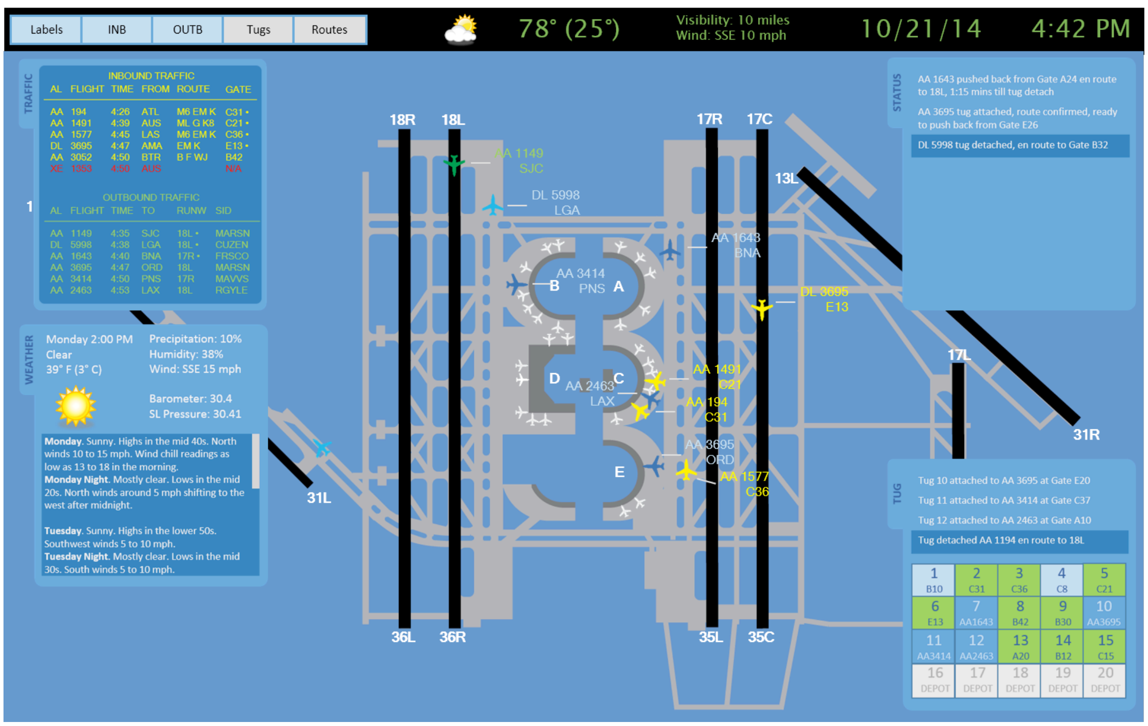


Figure 23: The second iteration of the prototype SAFETug-ASDE-X display.

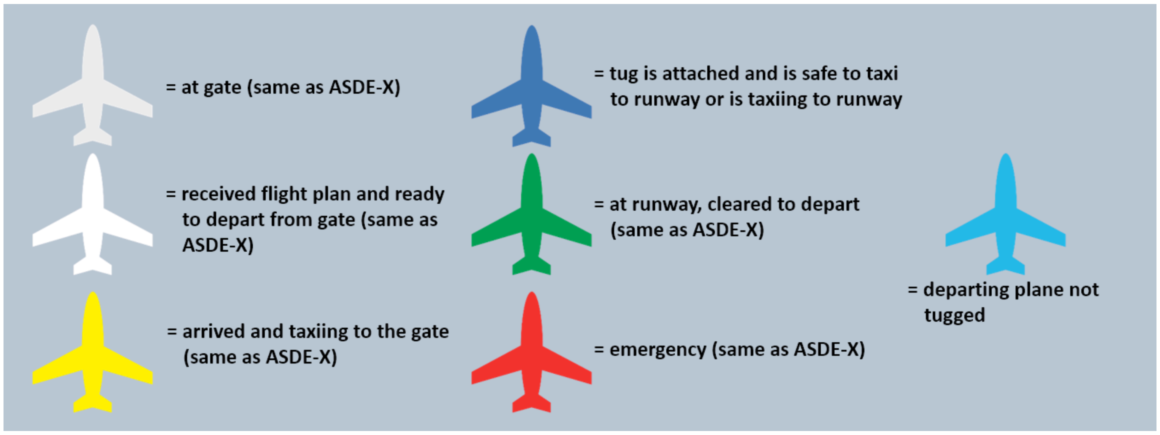


Figure 24: The refined aircraft color and status for the SAFETug-ASDE-X display.

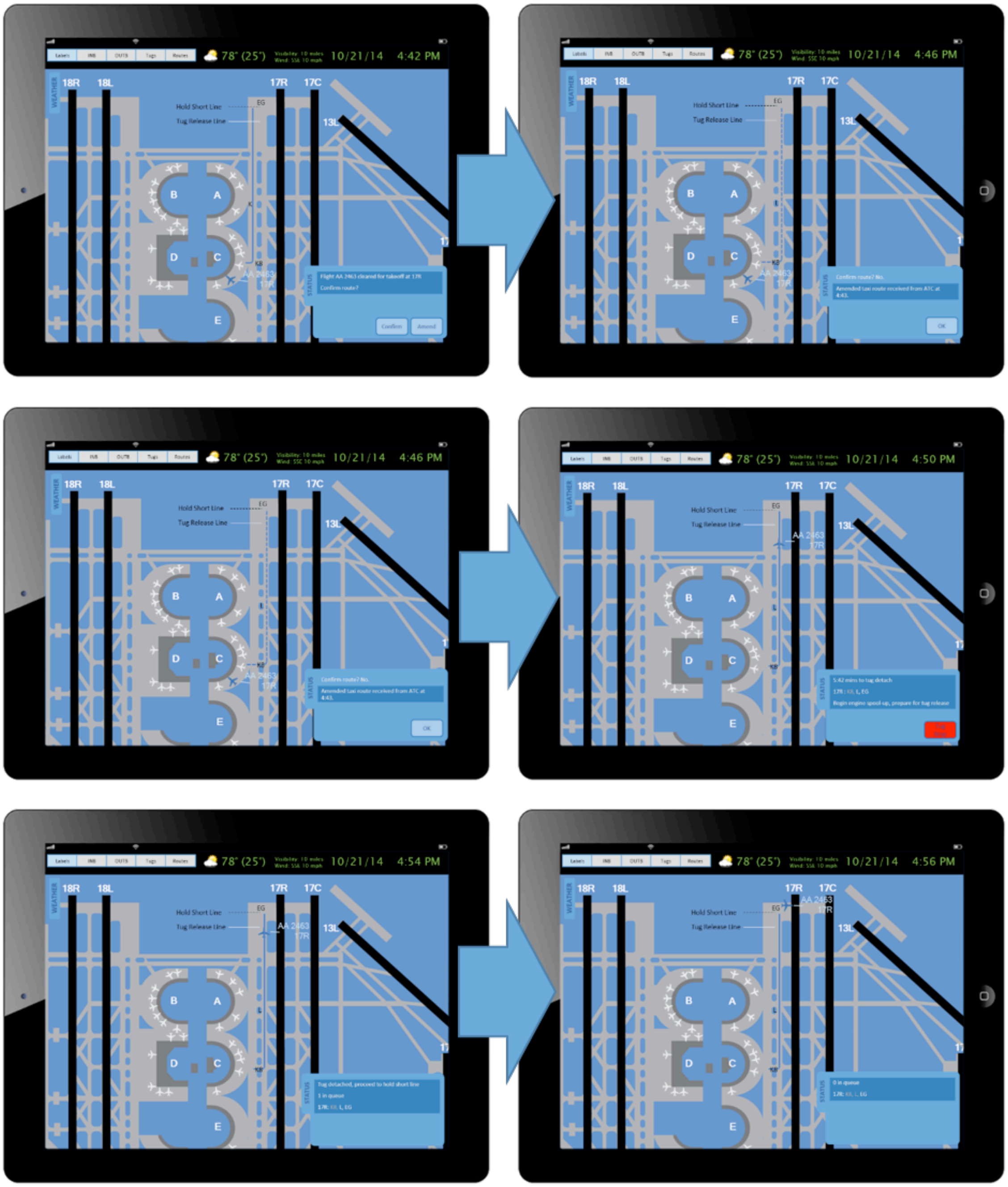


Figure 25: Updated pilot displays based on heuristic evaluations.

A final set of structured interviews were conducted on the updated displays using domain experts. However, the team was unable to analyze and update the SAFETug-ASDE-X Display and Pilot Display prior to completion of this effort. The data provided from this final evaluation is include in Appendix I: Final Heuristic Evaluation and will be analyzed as part of a future effort.

4.3.5. INTERACTIVE PROTOTYPE

A low fidelity interactive prototype of the SAFETug ASDE-X display was also developed using HTML5. The goal of the interactive prototype was to be used as an interactive storyboard, simulating the flow of information from the SAFETug system to the controllers. This approach provides a way for domain experts to experience parts of the system in a realistic manner without there being a fully developed environment. Using this approach allows greater feedback on the interface and interactions between the controller and SAFETug system and thus allow for better mapping of interface elements to controller expectations. The interactive prototype developed for this effort is focused on a nominal departure scenario. The team did not have the opportunity to use the interactive prototype in the aforementioned evaluations, however it will be a useful tool for future evaluations.

5. Tug Autonomy

5.1. Autonomy Requirements / Design

In this section, we describe the efforts taken to derive the initial set of requirements identified during this seedling. Where possible, we have also identified hardware and software elements that would be required to implement a safe, robust, and low-cost autonomy capability that minimizes acceptance risk by being a reversible applique onto existing manned platforms.

5.1.1.1. Requirements Drivers

First, **safety is our first priority – including safety with respect to people, equipment, and infrastructure**. In terms of Human-Machine Interaction (HMI), safety also includes not imposing additional cognitive workload or stress to humans that will be interacting with the tugs. The SAFETug Autonomy approach must ensure that pilots, marshals, etc. experience as little change in their procedures and expectations of the tug – whether it is manned or autonomous.

Second, we also want to minimize cost – both up-front and recurring. Complementing cost is perceived risk to adopters. To mitigate this, we intend to make the tug adaptation reversible. Tugs by themselves are very expensive and the ability to revert them back to normal manned operation would be highly desired by potential early adopters.

And of course, the system should be effective in the areas for which it was intended – including improvements in logistics and the operational cost associated with ground operations. The list of requirements drivers is summarized below as a series of goals.

5.1.1.1.1. Safety Drivers

- **Human** – Autonomous Tug must be safe to operate near people
- **Equipment** – Autonomous Tug must not pose a physical (mechanical, electrical, etc.) threat to infrastructure, vehicles, etc.
- **Continuity**– Autonomous Tug must not be disruptive to existing procedures for ground operations

5.1.1.1.2. Cost Drivers

- **Up-Front** – Applique must not have a high cost of entry
- **Recurring** – Applique must not be financially burdensome over time
- **Reversibility** – Applique must be able to be completely removed and tug restored to normal manual operability

5.1.1.1.3. Effectiveness Drivers

- **Logistics Improvement** – Measurable positive impact to logistics
- **Cost Improvement** – Measurable reduction in cost related to fuel consumption by aircraft while on the ground

5.1.1.2. Basis Host Tug

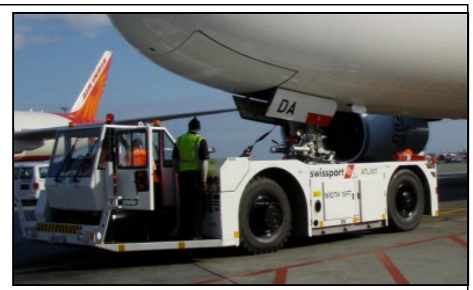
We have identified the **AeroTech Expediter 600** as the likely best candidate for an initial host platform. We have selected this tug as it presents the best tradeoff between range of aircraft it is capability of towing and the reduced degrees of freedom that the towbarless variety of tug

Figure 26: Selected Basis - AeroTech Expediter 600

presents. This simplifies the attach/detach functions that the autonomy needs to perform.

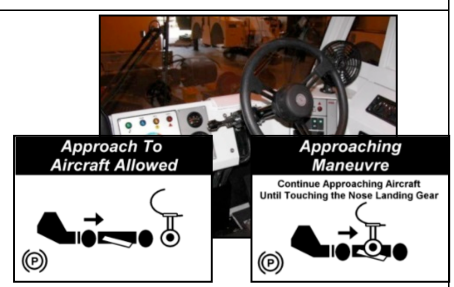
5.1.2. Capabilities

- Wide-Body Aircraft Pushbacks and Maintenance Tows
- Aircraft Range: A300/B767 through A380
- Top Speed: 28 km/hr (17 mph)
- Four (4) Wheel Drive, Two (2) Wheel Steer
- Power Source: Mercedes OM 502LA V8, 420 kW (563 hp)



5.1.3. Control System

- Clean Dashboard Concept
    - Simplest controls in the industry
- Automated NLG Pick-up Sequence
    - Single joystick control and interlocks
    - Automated procedures
    - Detailed instructions on PLC screen



5.1.4. Automatic Aircraft Selection

- Fail Safe Proximity Switches Detect Nose Wheel Size
- Automatically Adjusts:
    - Maximum tractive effort
    - Maximum brake force
    - Oversteer Alert Device setting
- Minimizes Risk of Operator Error and Aircraft Damage

5.1.5. Attachment / Detachment

- Aircraft Landing Gear Locks Securely into the Tractor's Cradle
    - Accommodates raked NLG (6° swivel)
    - Positive top locking cylinders
    - Supports aircraft weight underneath the nose wheel
    - Interlocks prevent closing gates with the NLG partially inserted
    - Interlocks prevent completing cycle if NLG is improperly engaged
- Cradle Moves During Turns Taking Pressure Off of the Landing Gear
- Simple Design with Six (6) Hydraulic Cylinders

5.1.6. Operator's Cab

- Spacious Cab with Easy Access
- Excellent Visibility of NLG Pick-up and Surrounding Area
    - Elevating cab standard feature
- Dual Driving Controls
    - Rearward: Aircraft NLG pick-up, push backs
    - Forward: Maintenance towing
- Suspension Driver's Seat
    - Swivels 180°
- Well Insulated Cab
    - Low noise level
    - Tightly sealed, protects against jet blast
- Two (2) Passenger "Jump" Seats
- Optional Air Conditioning

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5.1.6.1. Autonomy Appliqué Design

Figure 2 shows a conceptual software and hardware design for the tug autonomy. We refer to this as an "appliqué" as our intent is to eventually integrate with existing tugs that a site already has available and for this integration to be fully reversible such that the tugs can be reverted to their previously human-operated condition.

The outer light gray "Tug Autonomy Appliqué" box in Figure 2 depicts a number of hardware elements providing the required processing, sensing, positioning, and actuation (moving the controls for instance) functions. As a part of the Appliqué, one or more processing elements (shown as a single Processing Element in the figure) will house the various software functions required for autonomy are depicted in the green boxes.

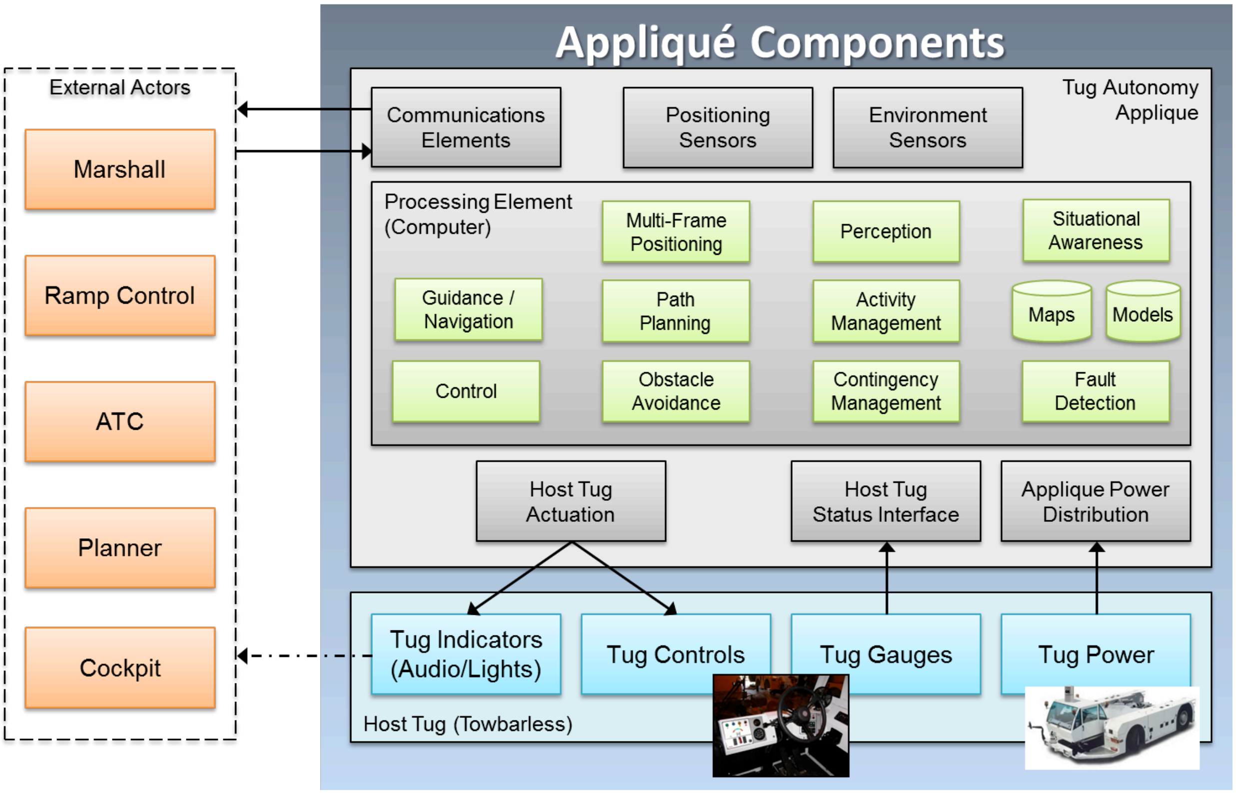

Figure 27: Key functional elements required for applying autonomy to tug operations.

One thing to point out with the design is the need for maintaining multiple coordinate frames. This is driven by the fact that the autonomy will be performing many functions that are best performed in a coordinate frame that is relative to some dynamic entity such as the plane, landing gear, or even the tug itself. The details of the required coordinate frames and their maintenance can be found in the separate task report covering perception algorithms, but to summarize, the tug will need to maintain at least the following frames:

- **Geodetic Reference Frame:** This frame defines where the tug believes it is in WGS-84 GPS/Geodetic coordinates. It is often referred to as the "world frame".
- **Map-Relative Reference Frame:** This frame define where the tug believes it is relative to a digital map that is commonly shared across other systems.
- **Aircraft-Relative Reference Frame:** This frame defines where the tug believes it is relative to some point on the plane. Notionally, this will be the nose of the plane with one of the axes parallel to the centerline of the plane body and passing through the tip of the nose.
- **Wheel-Relative Reference Frame:** This frame defines where the tug believes its grasping apparatus is relative to the fore landing gear. This frame may be the same as the Plane-Relative one, but its primary source of localization information will be the rear-facing camera.

- **Tug-Relative Reference Frame:** This frame defines an ego-centric frame that moves with the tug. The active sensors and sensor processing functions such as the LIDAR and EO/IR-based tracking will report data in this frame. Notionally, this is the frame within which the obstacle detection and avoidance functions will work within.

Any processing related to the reference frames must be cognizant of the localization error within those frames. For safety reasons, prognostic and risk avoidance behaviors should be invoked whenever localization error grows beyond a tolerable threshold (TBD).

5.1.6.2. Vehicle Dynamics and Control

The dynamics of the tug and the two-body tug-plane are still left for further investigation. Some requirements have already been defined during Task 1.1 and were presented in its summary report. Future work would need to investigate approaches to the unique of autonomous tugs through high-fidelity simulation and where possible, physical experimentation. These include:

5.1.6.2.1. Steering Control

The tugs themselves are not a conventional vehicle and when towing an aircraft, you have a two-body problem where overall mass and physical constraints at the grasping point need to be fully understood before defining the low-level control loops. New guidance functions would need to be implemented beyond simple trackline following to deal with situations such as avoiding an obstacle or broken pavement while in tow.

Autonomous push-back is not a well explored problem for autonomy. The two-body aspect can even be difficult for humans and there has so far been little need to study this for practical autonomy applications.

5.1.6.2.2. Acceleration and Braking

Many of the same issues for steering affect the approach for acceleration and braking. This is especially true for the masses involved when you factor in the stress limits, and the goals to minimize transit time and energy required. The physical limitations of the systems and hardware define the times and distances needed for braking and accelerating to desired speeds.

5.1.6.3. Sensing Requirements

The ability of the tug to sense and perceive its environment is, of course, critical to its safe operation. However, for practical reasons, we must constrain the cost and complexity of the system in order to be affordable. Therefore, during this seeding we performed a set of trade studies and initial investigations into the software and hardware requirements needed to operate safely. These included:

- Trades on the placement of commonly used classes of sensors (LIDAR and Electro-Optical / Infrared cameras) on the selected host tug
- Data collection at actual airports using those classes of sensors
- Analysis of the data collected to ensure it can be used for safe, real-time operation

- Identification of required processing functions to turn sensor data into a world model amenable to autonomous decision making, planning, and guidance functions
- Correlation of autonomous perception requirements to systems with similar needs to identify minimum hardware requirements

Summaries of the activities follow below.

5.1.6.3.1. Tug LIDAR Placement

The first placement trade we performed involved the placement of a LIDAR with the goal to maximize coverage near the tug and out to the required safety threshold distance of 100m for tracking objects in the environment. We sketched up a rough 3D model of the Expediter tug and then used raycasting to look for gaps in sensor coverage that must be addressed. We tried different configurations of a single LIDAR and then two LIDARs in both balanced and unbalanced arrangements, but always found that we could not cover areas of the ground near the tug due to shadowing. This presents a safety issue to any person walking nearby as the tug would not be able to sense them.

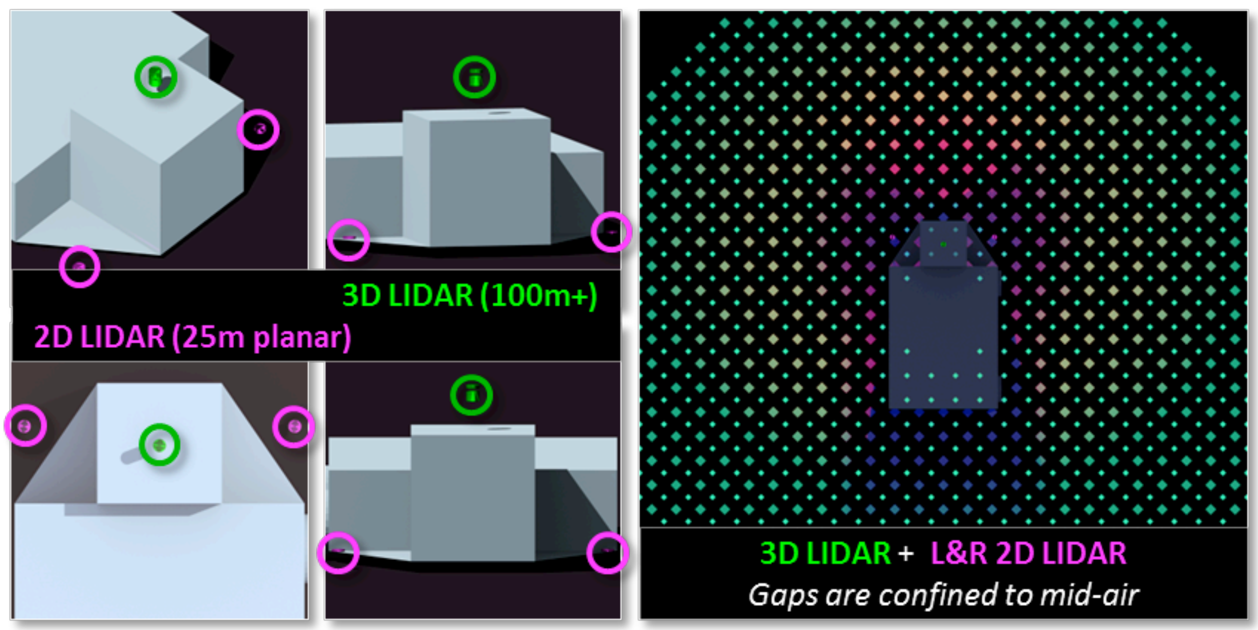

Figure 28: Left – Placement of single long-range 3D LIDAR on the tug cab (green) and dual short-range planar LIDARs closer to the ground (pink/magenta). Right – top-down view showing areas covered by each sensor. Yellow tones indicate coverage by both types of sensors.

We then investigated the use of multiple less-expensive LIDARs with the caveat that they typically have a smaller field of view and shorter range. Using the more capable LIDAR to cover sensing out to the maximum required distance, we can use just a handful of the less capable sensors to look for people and obstacles near the vehicle. Focusing on the gaps left by the primary LIDAR, we were able to come up with a configuration that should detect anything human-sized or larger within proximity to the tug using inexpensive "planar-only" sensors.

This configuration, when combined with the cameras described in the next section, should provide ample coverage near the tug.

Our suggested LIDAR placement approach is thus:

- Use single 3D LIDAR for area coverage.
- Fill in the gaps near the vehicle with 2D planar LIDAR(s), which are often less expensive.
- LIDARs can be extended from the vehicle, but not impact its ability to navigate through its areas of operation.
- Small gaps may still be present due to shadowing /occlusion of the LIDARs by the tug body.
- Gaps must be smaller than a human or present no danger to humans during normal operation.

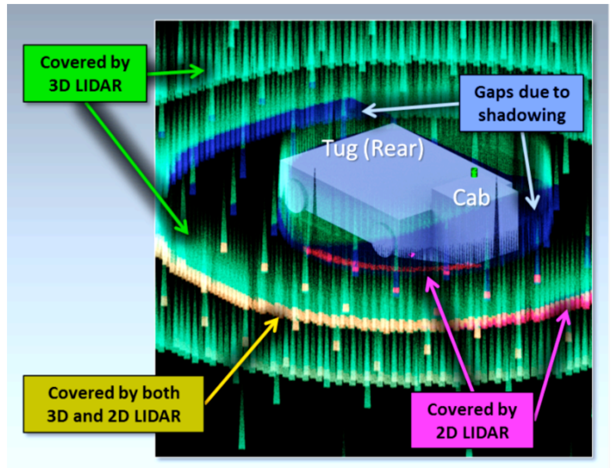

Figure 30: Gaps in front of the tug have been minimized.

5.1.6.3.2. Tug Camera Placement

This describes the electro-optical / infrared camera placement we believe will both provide adequate positional information for attach and detachment functions and will cover any remaining gaps to the rear of the tug left over from the LIDARs.

Our suggested approach is shown in Figure 6 and can be summarized as follows:

- Backup camera on opposite side from normal tug operation
- Cross-view camera provides better estimation of distance remaining
- Cross-view can be matched to known acceptable wheel positions prior to activating lift
- Both cameras can be used for tracking IR signatures to provide coverage in LIDAR shadows of human activity

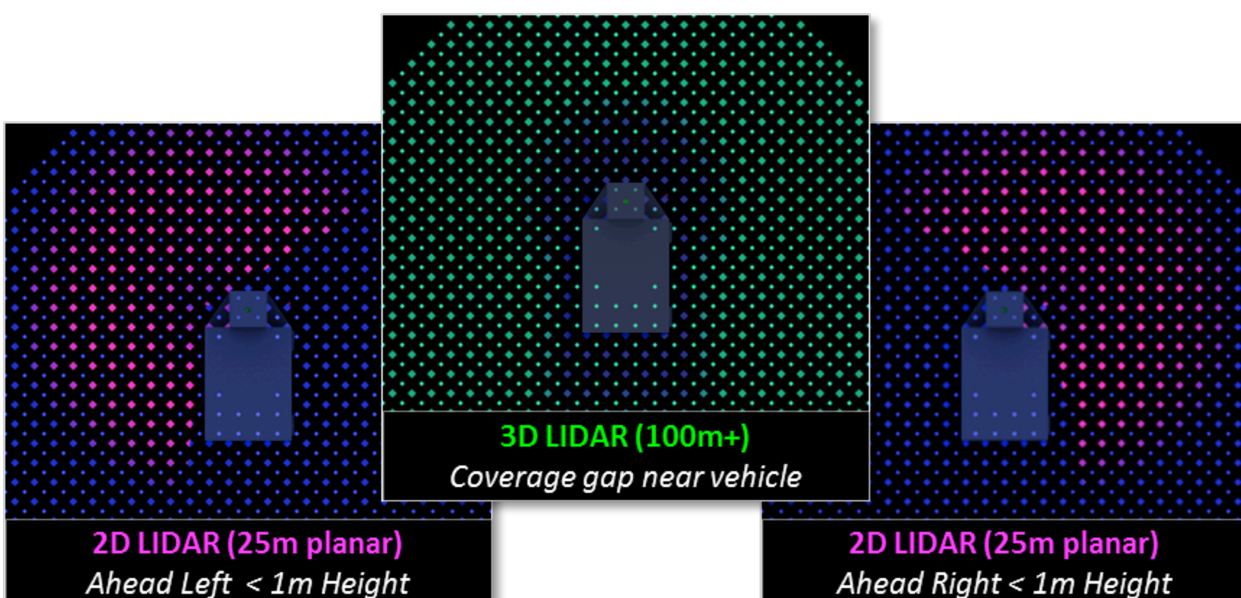

Figure 29: Top-down view showing the individual coverage areas of the three LIDARs in the proposed

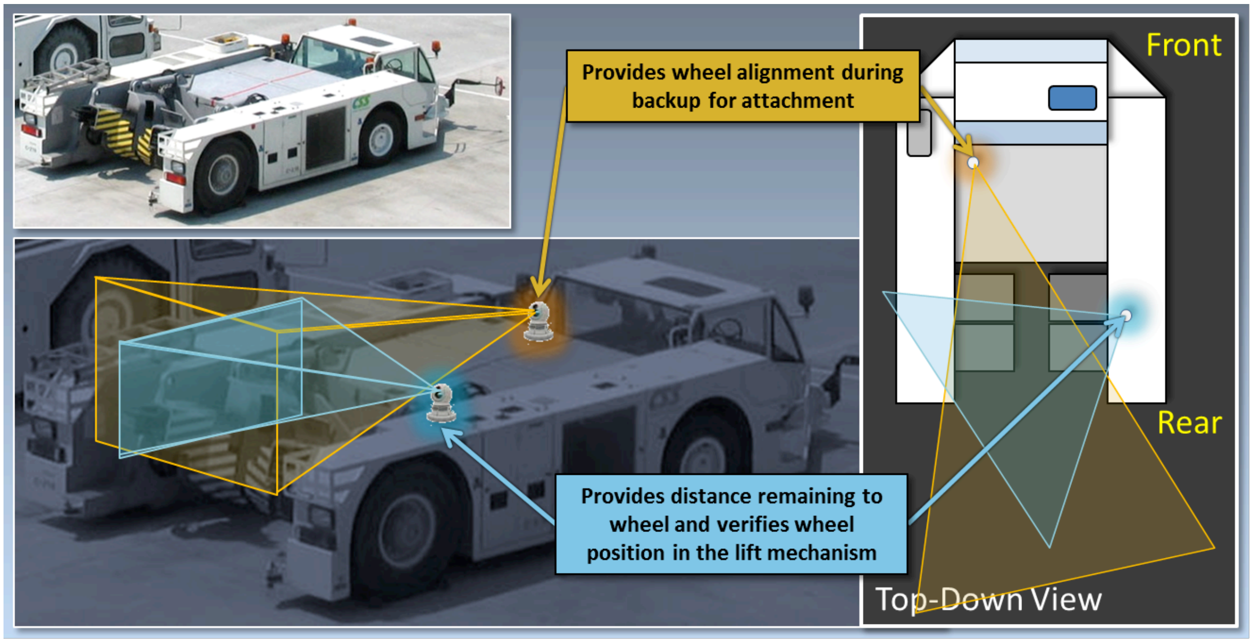

Figure 31: Dual Electro-Optical / Infra-Red (EO/IR) Camera Placement

Our focus for the latter parts of the combined LIDAR and camera placement analysis was to ensure that the tug can detect people in proximity to the tug under any reasonable circumstance. With the configuration we have proposed, *a person would have to be doing something way outside of normal procedures to not be detected.* In these cases, it is assumed that someone would be aware of these activities and have either already disabled the autonomy or would be monitoring and be able to invoke an emergency stop of the tug if needed.

5.1.6.4. Sensor Data Collection & Analysis

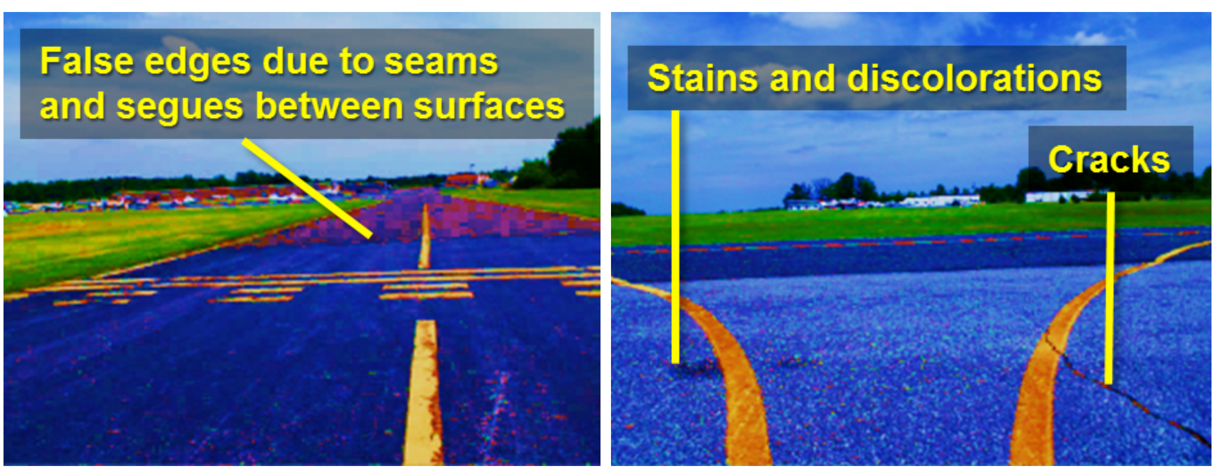

Figure 32: Stains, Cracks and Seams

We performed two data collections to during this seedling to aid with the sensor trade studies. In particular, we wanted to:

- Confirm that the initial class of sensors we anticipated to use would provide sufficient information to safely operate the tug autonomously
- Understand the operating environment itself
- Use our understanding to derive the perception requirements (software and hardware)
- Use our understanding to derive initial guidance-, navigation-, and control-related requirements
- Use our understanding to confirm initial safety-related requirements and derive new ones as needed

5.1.6.5. 2D Video / Imagery Data

The first data collection event gathered video and imagery at the South Jersey Regional Airport.

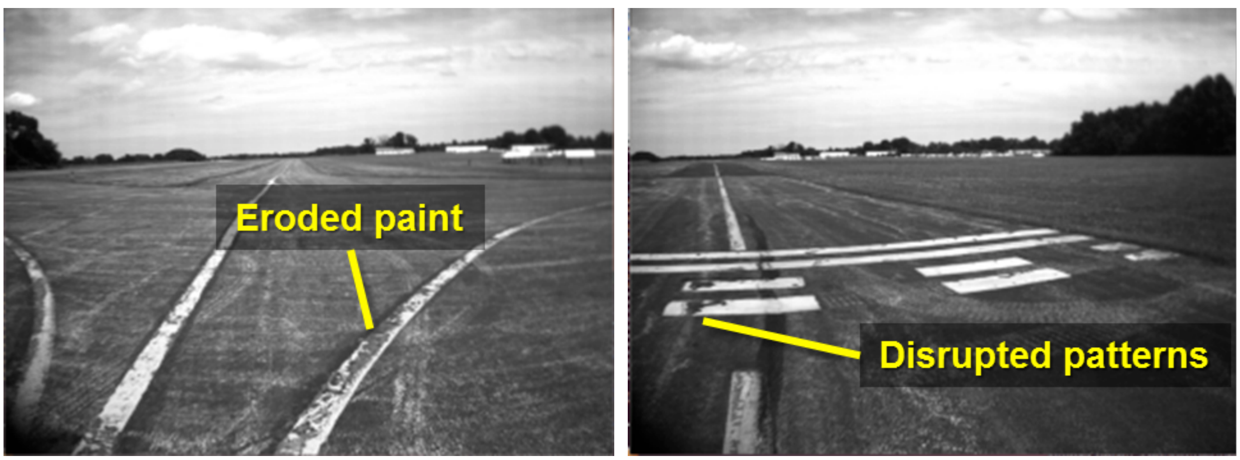

Figure 33: Eroded and Disrupted Paint Markings

The second collected LIDAR data at the Atlantic City Airport around the gate areas.

The imagery and video collected highlight many of the challenges for autonomous perception. Weathering and wear such as that shown in Figure 8 and Figure 7 on the tarmac surface results in features that must be filtered out. Some can be confused with expected features (paint lines, etc.) with similar aspects (linearity, width, contrast with surroundings, etc.). For instance, a long crack could be confused in some cases with lane markers if it is sufficiently straight and no color information is available. Gaps in expected features can also be problematic as they present breaks in continuity that should be bridged.

There are well-studied methods for filtering out various features on surface streets and the state of the art for self-driving cars provides much of the required functionality. One exception, however, is operating in degraded weather conditions. Manned tugs currently operate in conditions that self-driving cars cannot currently handle. To achieve this capability, we intend to exploit the fact that our we will be operating in a well structured environment in which nearly all of the players will be communicating on a regular basis with position updates. In addition, we assume that detailed digital maps will be available for any large commercial airport. We can use these maps as priors against which we can register any detectable features to mitigate this problem. Under any operable conditions, this also allows us to localize ourselves relative to the maps and thus lessen the requirements for high-resolution high-availability GPS positions.

5.1.6.6. 3D LIDAR

We also collected LIDAR data at the Atlantic City Airport. Using 3D point cloud visualization and playback tools as depicted in Figure 9, we analyzed the collected data to look for useful features we can exploit for autonomous operations. With relatively simple filtering, we were able to clearly separate features that the perception system can use to aid autonomy.

Our focus was on identifying geometric shapes to be matched with models of objects we would expect to encounter in the environment. However, we found that we can also detect surface features (Figure 10) with the LIDAR such as paint patterns on the ground and highly-reflective materials such as those found on safety vests and emplaced cones.

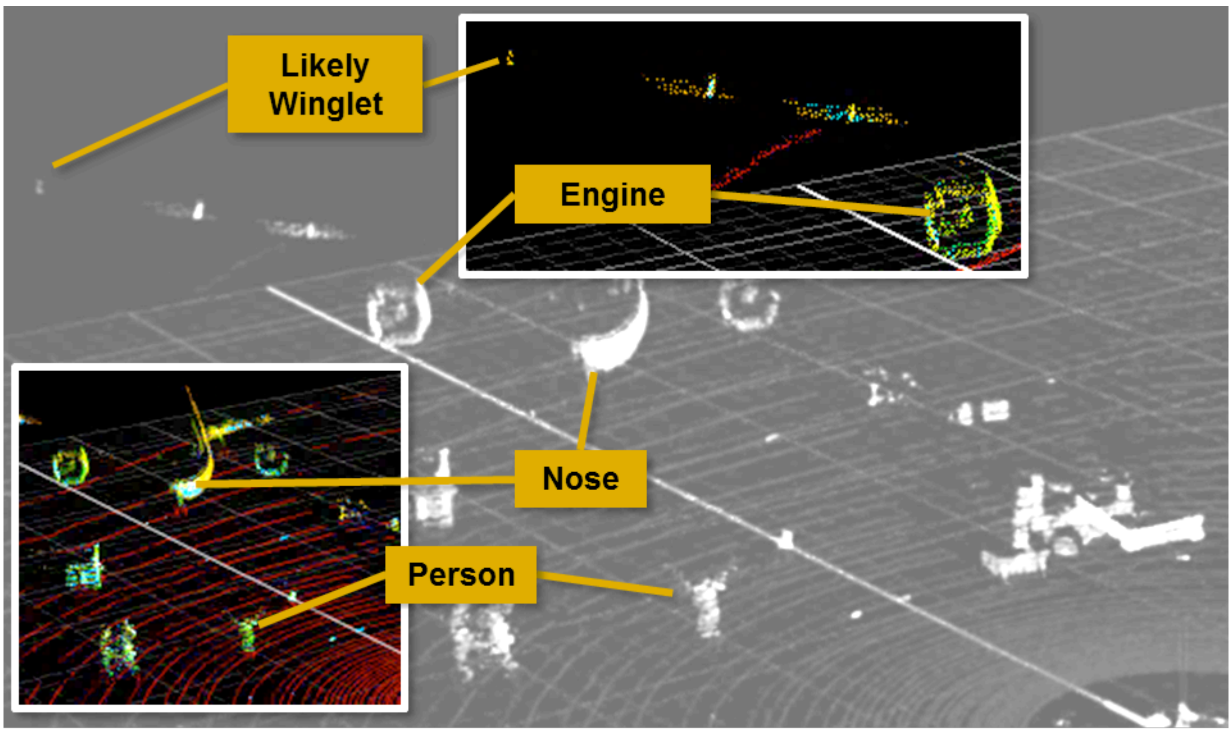

Figure 34: LIDAR analysis showing filtering and candidates for geometric matching.

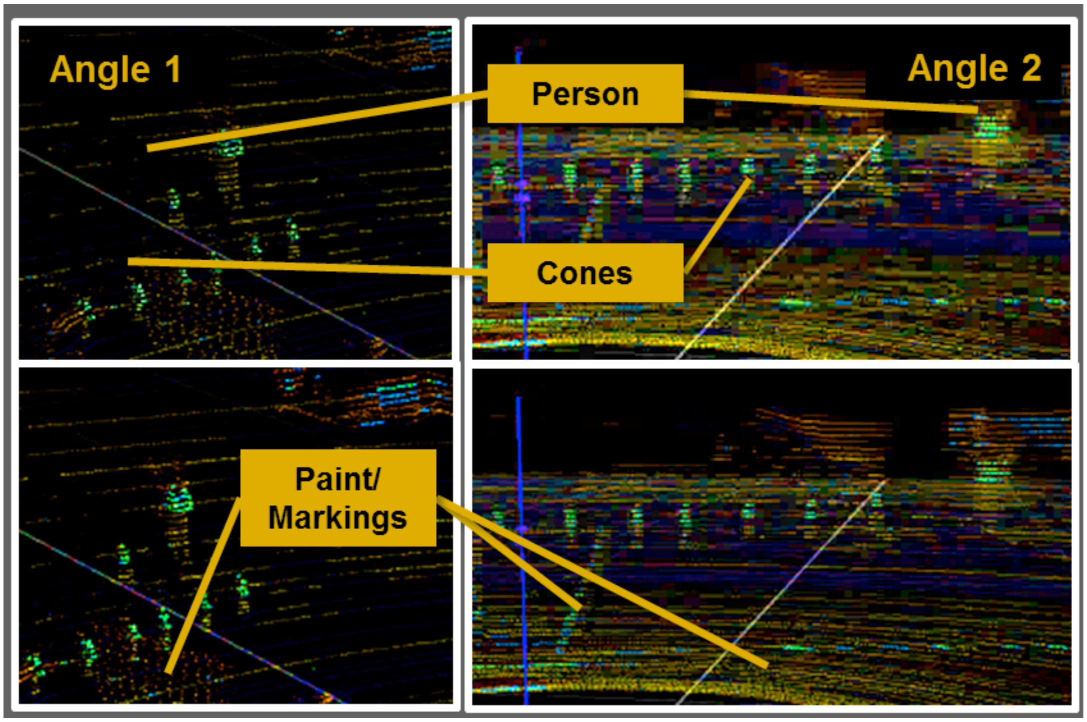

Figure 35: LIDAR analysis showing filtering by reflectivity to highlight people wearing safety vests and detectable surface markings.

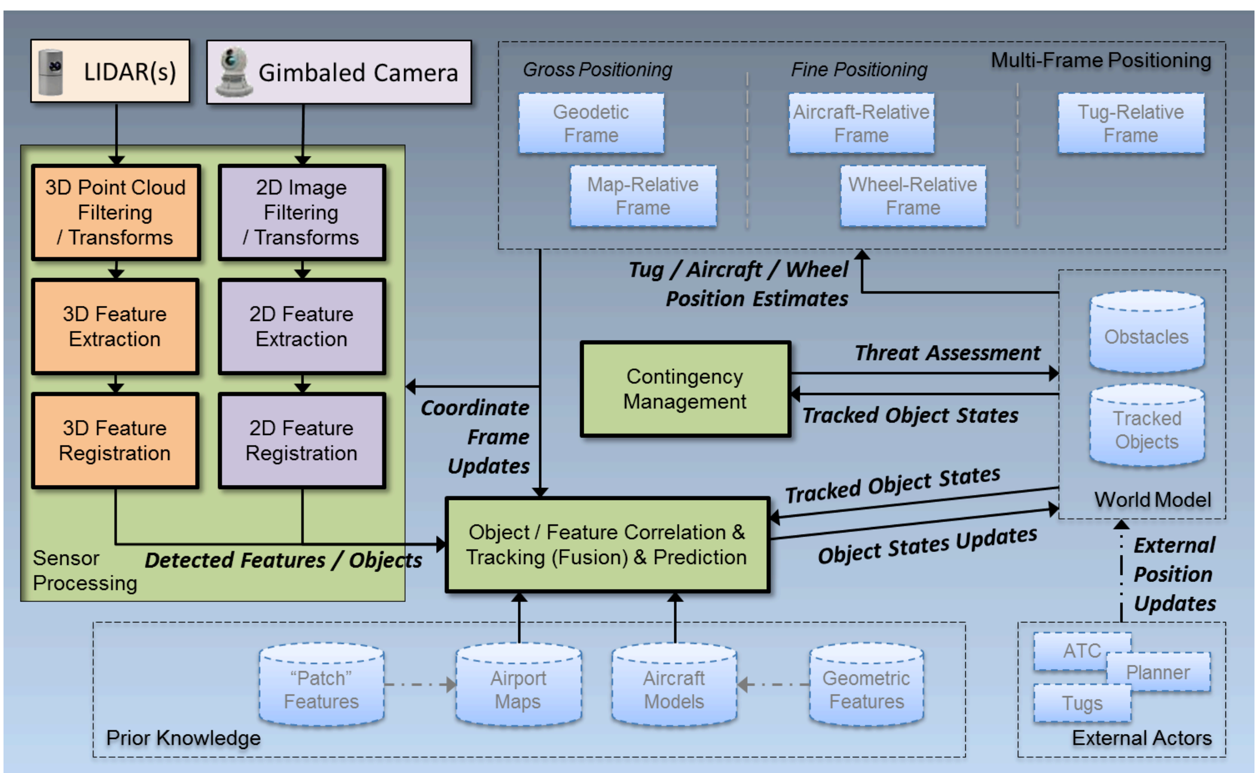

Figure 36: Sensor Data Processing and Flow

5.2. Notional Perception Architecture

In concert with performing the sensor trades and data analysis, we defined a high-level architecture (Figure 11) that we believe is capable of performing the required processing to turn sensor data into actionable situational awareness information. Using this architecture as a reference, we've partially decomposed the perception software components into required processes and algorithms to fulfill each component's functionality. Where possible, we've identified candidate software configuration items that can be leveraged to implement the functionality in this design.

Using this functional flow as a guide and pulling from prior experience, we have identified a list of sub-functions that would be required for implementation as well as a few candidate software packages. These are described in Section 5.3.

5.3. Required Perception Functions

The list of required perception functions and algorithms and candidate software packages follows:

2D EO/IR Video Processing

- Edge detection (Canny or similar)
- Line/Curve detection
- Ground plane registration
- Affine transform from ground plane
- Fourier transform + pattern match
- IR-band filtering / blob tracking
- Image / Video Segmentation
- Feature matching / image recognition (wheels, nose, etc.)
- Distance estimation

3D LIDAR Point Cloud Processing

- RANSAC – Geometric primitive matching
- RANSAC – Map/model alignment/registration
- Reflectivity filtering
- Ground plane extraction (likely RANSAC)
- Fourier transform + pattern match (on ground plane)
- Point cloud segmentation + noise filtering

Object / Feature Correlation and Tracking

- 2D object tracking / registration
- 3D object tracking / registration
- Multi-lateration / correlation (2D → 3D track conversion)
- Multi-source track correlation
- Track prediction

Positioning & Navigation, Contingency Management, Other Required Capabilities

- Maintenance of navigation frame transforms (tug-relative ←→ geodetic, etc.)
- Obstacle detection, tracking, and incursion threat assessment
- Anomaly detection (bad wheel positioning, sensor failure, etc.) and impact assessment

Candidate Software Packages

- OpenCV – general purpose computer vision library
- Point Cloud Library (PCL) – utilities for processing 3D LIDAR data
- LM-ATL's Track Data Fusion – robust, multi-source object tracking and prediction
- OpenNI (optional) – utilities for extracting human pose / gestures from sensor data

To aid in our future hardware trade studies, we performed some analysis on which perception functions would require the greatest processing resources using both CPU and Memory as a single "Load" factor. Based on prior experience, we know that some of the point cloud processing functions – in particular, maintaining a consistently tracked group of points (via 3D Object/Point Registration) – is by far the most demanding. We then performed a quick comparison with existing work to get an estimate of the hardware required.

Based on this comparison, we have concluded that the equivalent of an 8-core 2.8GHz Intel Core i7 and 32GB of memory would be the minimum for successfully executing the required perception functions. Further improvements can be made by utilizing the GPU if available for vector / matrix operations. The processing hardware used is relatively inexpensive and commercial off-the-shelf. To provide a sufficient engineering buffer, we would expect to use at least slightly more capable hardware than depicted here, but the change in cost would likely be negligible.

5.3.1.1. Obstacle avoidance

In our investigation into an approach for obstacle avoidance, we found that the needs for SAFETug are quite similar to that of prior work in underwater vehicles, but with two key differences. The first is a matter of scale. If you look at cases where we have applied autonomy to surveys within long and narrow corridors such as pre-lay surveys for undersea pipelines, the problems are almost identical if you scale the speed and sensor ranges up by a factor of five. Acceleration, braking, and heading control are similarly scaled up for the tug from those of the underwater case.

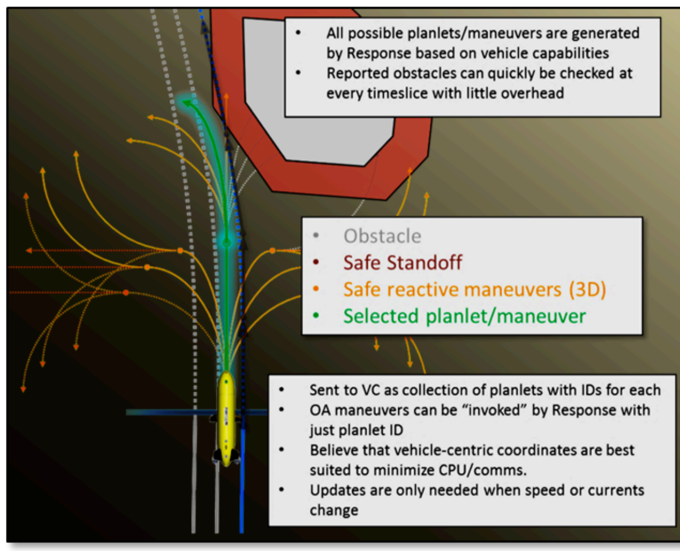

Figure 37: Obstacle avoidance as implemented on commercial autonomous underwater vehicle (AUV)

The second and most important difference is the two-body problem when in tow, which is still a topic for further investigation, but would likely still be amenable for leveraging our prior work for obstacle avoidance. To summarize:

- Obstacle / Threat Avoidance similar to autonomous underwater surveys
    - Braking, especially during towing, not easy
    - Nominal speed of the Tug roughly 5x that of compared underwater vehicle
    - Sensor range of Tug > 5x of the underwater vehicle
- Long plan segments are subdivided into smaller tracklines as needed to minimize deviation from the planned path
- Avoidance behaviors communicated back to the planner and shared with other tugs and tug mode indicators updated

5.3.1.2. Contingency Management

Finally, what we refer to as “contingency management” has been a very useful paradigm for dealing with unexpected situations. These situations can be as low as a hardware failure all the way up to team-level logistics issues. Contingency management provides a framework for keeping these events localized as much as possible, but able to escalate from subsystem, system, vehicle, to offboard the vehicle to teammates or human operator.

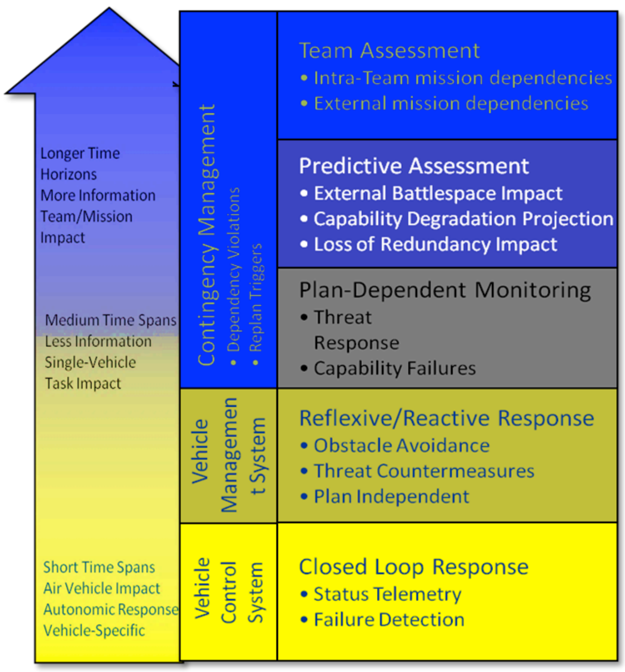

Figure 39: Effective Contingency Management increases reliability and robustness of unmanned systems and reduces human workload

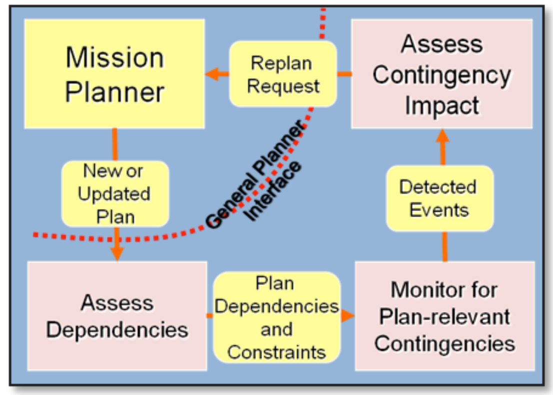

Figure 38: Contingency Management interacts with the vehicle-borne planner to quickly adapt to the situation.

6. Conclusions

The goal of this effort was to explore how a HMI for SAFETug could be developed that would calibrate trust, maintain SA and reduce workload for ATC/Ramp controllers and pilots. To accomplish this, the team explored current AOA processes, used an EID and HTA to design prototype HMI's for controllers and pilots and finally performed heuristic evaluations. Tables 1, and 2 show how the SAFETug HMIs support an appropriate level of trust, and SA; it also notes potential areas of future work for each of these areas. The design recommendations for trust are from Hoff and Bashir's review of recent empirical research on factors that influence trust in automation (Hoff & Bashir, 2014). The SA design recommendations for supporting automation is from the Oxford Handbook of Cognitive Engineering (Lee & Kirlik, 2013). To support appropriate workload, we used EID design principles.

Table 1. SAFETug HMI design features that support appropriate trust (Hoff & Bashir, 2014)

Design Feature	Design Details	SAFETug HMI
Appearance/anthropomorphism	Consider the expected age, gender, culture, and personality of potential users because anthropomorphic design features may impact trust differently for diverse individuals	Future research
Ease of Use	Simplify interfaces and make automation easy to use to promote greater trust	Build upon already existing systems and layouts. This will allow for transfer of training and match with existing mental model of interface operations. Performed heuristic evaluations with SMEs. Results indicated that the HMI is simple and easy to use.
	Consider increasing the saliency of automation feedback to promote greater trust	Automated Planner/Scheduler's and tugs' status are displayed graphically (icons, routes) and textually (tabs).

Communication Style	Increase the politeness of an automated system's communication style to promote greater trust	All routes are suggestions and not commands.
Transparency/Feedback	Provide users with accurate, ongoing feedback concerning the reliability of automation and the situational factors that can affect its reliability in order to promote appropriate trust and improve task performance	Automated Planner/Scheduler's and tugs' status are provided.
	Evaluate tendencies in how users interpret system reliability information displayed in different formats	Future research
	Consider providing operators with additional explanations for automation errors that occur early in the course of an interaction or on tasks likely to be perceived as "easy" in order to discourage automation disuse	For this first year effort, we are focusing on only nominal departure scenarios.
Level of control	Consider increasing the transparency of high-level automation to promote greater trust	Automated Planner/Scheduler's and tugs' status are provided.
	Evaluate user preferences for levels of control based on psychological characteristics	Heuristic evaluations provided us with some information about the appropriate level of control

Table 2. SAFETug HMI design features that support appropriate SA (Lee & Kirlik, 2013)

Design Feature	**SAFETug HMI**
Automate only if necessary	Minimizing changes to the current airport operations by building upon already existing systems and layouts.
Use automation for assistance in	SAFETug suggests routes using the same information

carrying out routine actions rather than higher-level cognitive tasks	ATC/Ramp controllers use when determining taxiing information thus we limit this the controllers need to decide on routes.
Provide SA support rather than decisions	SAFETug's status along with, weather, and flight information are all provided to aid the HMI controller. HMI controller and flight deck team still follow current FAA guideline of confirming routes. Use typography to create hierarchy and clarity. Different sizes, fonts, and arrangement of the text help increase scanability, legibility and readability.
Keep the operator in control and in the loop	The SAFETug's system status are provided to the controllers and pilots.
Avoid the proliferation of automation modes	The tugs have a single automation mode. The HMI provides emergency controls such as emergency stop.
Make modes and system states salient	The SAFETug's system status are displayed graphically (icons, routes) and textually (tabs)
Enforce automation consistency	Prompt are the same throughout the systems
Avoid advanced queuing of tasks	In the later HMI displays the routes are provided to the controllers on a first come basis thus minimizing the clutter of the display.
Avoid the use of information cueing	All tabs can be minimized.
Use methods of decision support that create human/system symbiosis	SAFETug is a decision support aid. It does not automatically assign routes but instead suggest optimal routes and waits for confirmation from ATC/Ramp
Provide automation transparency	The SAFETug's system status are displayed graphically (icons, routes) and textually (tabs)

7. Summary

This report has presented the idea of semi-autonomous engines-off taxiing, through the application of self-driving vehicle technology to enabling an automated taxiing system at busy airports. Aside from the technical problems of autonomous navigation, sensing and communication, the approach presented here recognizes the logistical challenges to be faced by autonomous engines-off taxiing. Adding a fleet of towing vehicles to the surface area immediately increases the traffic density on the surface, creating the potential for more delays. Secondly, the overhead of autonomous attachment and detachment also threatens to reduce the efficiency of operations by adding further delay. Third, the complexity of human-machine interaction in a dynamically changing environment threatens the efficiency of human decision-making. Despite these challenges, the solution presented here offers the potential for higher precision navigation, thus restoring at least some of the efficiency lost through increased surface density; decrease in human workload to pilots and controllers through automated decision making; and finally, the economic and environmental benefits that arise from engines-off taxiing.

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9. Appendences

9.1. Appendix A: Site Visit & Pilot Notes

Hobby (HOU) Air Traffic Control Visit

Date of visit: 2/21/14

Attendance: Vince, Ron, Mai Lee, Shelby and Kerry

ATC POC: Phillip

Notes

Research look-ups:

- American Airlines research on tugs

Future tours:

- Southwest operations at Hobby

Unanswered questions:

- What is the tug to gate ratio?

General information:

- Types of planes:
    - Air carrier: has over 70 seats
    - Air taxi's: smaller than 70 seats
    - Time share
- Zipper line
    - Separates movement area from non-movement area
        - Movement area (outside the zipper)
            - When in the movement area pilots have to be authorized by local/ground
            - FAA controls movement area
        - Non-movement area (inside the zipper)
            - Inside the zipper includes being at the gate
            - Don't have to talk to ground
                - Even though pilots are not required to talk to ground but good practice to call ground. Ground can provide information when safe and unsafe to push.

    - Once a pilot pushes back the plane may block another plane from getting to a gate.
    - Ground does not want to take control of non-movement/black area because they can't always see that area.

- Ramp control
  - Larger airports typically have ramp control
    - United has ramp control at IAH
    - Hobby does not have ramp control
- Dump box
  - Ground has to keep out-going planes out of this area (1/4 of a circle)
- Hobby
  - One of the most difficult airports for ATC
    - Have to use same runways for takeoffs and landings
    - Airports are not built like Hobby anymore
      - Part of the design was due to tail draggers needing to go into the wind
    - Favorite flow is south (do 70% of the time on 12 R or 22)
      - All 4 runways are active
      - Incoming will have to cross active runways
      - Try to use a take-off runway different than where planes are landing
      - Incoming and outgoing may pass on the parallels
    - Other flows:
      - East flow: non-Sunday
      - Church flow on Sunday's (due to noise constraints)
  - Only 40 – 50% scheduled flights --- reduces repeatability
    - A lot of corporate/taxi's
      - Cheaper to store planes
      - Close to downtown
  - Takes 51 seconds in turnaround time from runway to gate
  - Personnel in the tower (personnel will rotate between all positions)
    - Ground control
      - Organize the airport and orchestrate the flow
      - Pilots can't move at airport without permission
    - Tower/Local control
      - Owns the runways
      - Talks to radar controller (not located in the tower)
    - Clearance
    - Supervisor
    - Helo (helicopter controller)
    - Coordinator (not always present)
      - Used for extra help
    - Other personnel (non-colocated) work with:

            - Houston approach – making sure planes departing from Hobby don't hit arrivals into IAH
            - Center – only 20 centers in the country
    - ATC shifts – rotate every 2 hours and typically a 8 hr shift (some do 10 hr shifts)
        - There are formal handovers
            - Incoming controller has to do a pre-brief before doing handover with controller taking place of
                - Controller leaving has to stay on shift for X amount of minutes before leaving
- Other airports
    - Denver has an optimal setup
        - Arrivals in one way and exit on a different side
    - IAH
        - Has all scheduled flights (have slots) --- typical for larger airports
        - Picks departing runway by direction going out
- Money
    - Government
        - Gets money from multiple sources (fuel, parking, gate, etc.)
        - Would like to see a decrease in carbon emissions
    - Airline companies
        - Most airline companies make money on cargo and not transportation of people
        - Want to have more planes in and out
- Ground operations
    - Airplane company (e.g., American, Delta) may own their own equipment (e.g., fuel and food trucks)
        - Non-major companies (i.e., airlines that only have a gate at an airport) will pay other companies to use their equipment
    - Taxi speed is determined by the airline company; there is no range
- What happens if a runway closes
    - ATC tell ASDE runway closed
    - TRACON is updated
    - File a Notice to Airmen (NOTAM)
        - Published every 28 days
        - http://www.faa.gov/air_traffic/publications/notices/
        - http://en.wikipedia.org/wiki/NOTAM
    - When a plane is about 60 miles out the crew will call ATC and ask for conditions at the airport
        - This is the time ATC will let the crew know about runway closures (which they crew may or may not know about)
- What information ground uses to make decisions
    - Chooses what is safest and to keep planes moving

    - Decision variables:
        - Past experience
        - Experience of the pilot
            - 8 – 10 years ago there were a large number of vets to retire. Now there is less predictability in pilot actions and capabilities.
        - What runways are available
        - How busy is final (time of day)
        - Will the incoming plane have a delayed departure
        - Type of plane
        - Weather
        - What is the wind
            - Looking at the radar
            - Prefer a jet to go into a wind, but can do crosswind and can handle small tail wind (too much tail wind makes a plane fly to fast and may require more go arounds; a tail dragger can't do crosswind)
- Variability in the system
    - How a plane takeoffs is not always repeatability
        - Experience of the pilot
        - Load of plane
        - Personnel on ground
        - Wind
        - Taxiing speed
    - How a plane parks at gate
        - A bad pull in may mean that instead of 5 planes at gates there is only room for 4
            - Cost of concrete is expensive and an area that can be optimized
- Improvements
    - Reduce variables in the equation
    - Make every taxi repeatable (i.e., when ground says taxi the plane will taxi without delay (doesn't wait 30 secs.) and at the same speed each time)
    - Do not make change to drastic; ground is afraid of change

Tools used by ATC:

- Airport Surface Detection Equipment (ASDE)
    - Works like a radar gun
    - Used on the ground to tell where the planes are; can also pick up trucks
    - Accuracy of 8 ft.
- Standard Terminal Automation Replacement System (STARS)
- Airport Surveillance Radar (ASR)
    - Tells number of planes in the air
- Integrated Terminal Weather System (ITWS) - http://www.faa.gov/air_traffic/technology/itws/
- Technology that detects windshear (will sound when have windshear)

        - At clearance workstation
    - Terminal Radar Approach Control (TRACON)
        - http://www.faa.gov/about/office_org/headquarters_offices/ato/tracon/Information Data System (IDS) – like google
    - Instrument Landing System (ILS)
        - "radio beam transmitter that provides a direction for approaching aircraft that tune their receiver to the ILS frequency. It provides both lateral and a vertical signals. It is a ground-based instrument approach system that provides precision guidance to an aircraft approaching and landing on a runway, using a combination of radio signals and, in many cases, high-intensity lighting arrays to enable a safe landing during instrument meteorological conditions (IMC), such as low ceilings or reduced visibility due to fog, rain, or blowing snow." – source Wikipedia (2/26/14)
    - Digital (D-ATIS)
        - "continuous broadcast of recorded *non-control* aeronautical information in busier terminal (i.e. airport) areas. ATIS broadcasts contain essential information, such as weather information, which runways are active, available approaches, and any other information required by the pilots, such as important NOTAMs. Pilots usually listen to an available ATIS broadcast before contacting the local control unit, in order to reduce the controllers' workload and relieve frequency congestion.

          The recording is updated in fixed intervals or when there is a significant change in the information, like a change in the active runway. It is given a letter designation (e.g. *bravo*), from the ICAO spelling alphabet. The letter progresses down the alphabet with every update and starts at Alpha after a break in service of 12 hours or more. When contacting the local control unit, a pilot will indicate he/she has "information" and the ATIS identification letter to let the controller know that the pilot is up to date with all current information." – source Wikipedia (2/26/14)

Pilot tasks:

- Calls into ATIS (Automatic Terminal Information Service)
    - Each ATIS starts with a letter (e.g., B = Bravo)
    - A continuous broadcast of recorded aeronautical information (e.g., change in active runway)
- Files flight plan
    - Information for a flight plan is output on a departure strip that is used by ATC
        - Departure strips have information such as type of airplane, requested altitude, route
        - ATC informs the pilot if can proceed with the flight plan as planned or if there are modifications
- Receive information from company (e.g., gas)
- Clearance delivery (flight plan is validated and modified if needed)

    - Clearance it either sent digitally to the pilots or has to be read to pilots
        - Content on departure strips is what is communicated
- Pre-Departure Clearance (PDC)
    - Subscription service
    - A clearance that is issued in a text format instead of over the delivery controller's frequency; Pilot doesn't talk to anyone
    - General Aviation (GA) do not have PDC and have to get clearance from Air Traffic Control (ATC)
- Close door and ask for pushback from ground
    - Southwest (SW) wants pushback within 25 minutes. Other companies are 1 hour.
    - When pushback is requested, ground tells the pilot what runway to go
- Pushback
    - Individuals involved:
        - (Boss) Guy on headset connected to the airplane (sometimes walking or on tug)
            - Will stay connected to plane till captain says to disconnect
        - 2 wing walkers
        - Guy driving tug
- After pushback, start powering up
- Call ground and say ready to taxi
    - Ground will say which runway and how to get there
- Crew will taxi to hold short line
- Crew will request clearance for takeoff
    - ATC will provide clearance or tell to hold short

IAH Ramp Control Tour

Date of tour: 4/11/2014

Attendance: Ron, Shelby, Kerry, Mai Lee

Notes

POC's:

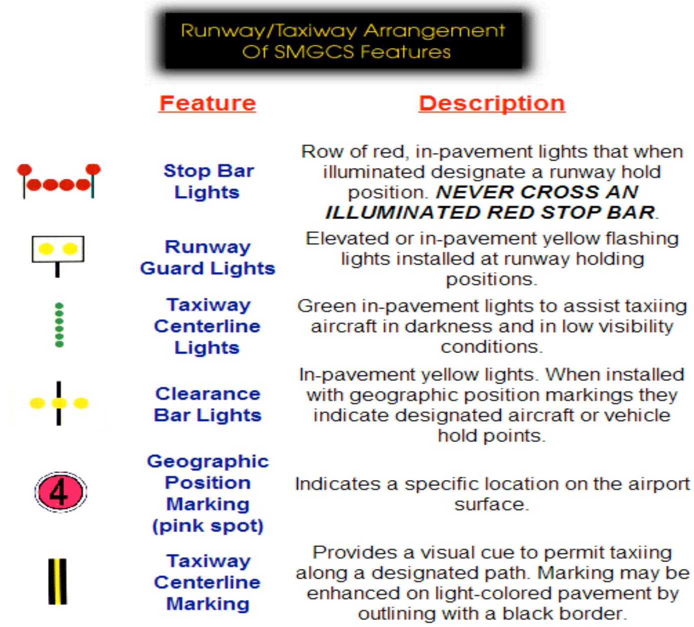
1) **Jeff Clark**
    a. Scheduled tour for team
    b. Ramp controller tour lead
2) **Louis Prebevsek**
    a. Male ramp controller
    b. Father works maintenance at DFW
    c. Prior experience as a ground operator

Technologies used:

- Aerobahn (http://www.saabsensis.com/products/aerobahn/):
    - Passive system so if planes turn off transponder, can't see
    - Cost is $2500 to equip tug with transponder so that can be seen with Aerobahn
        - Some tugs at IAH have transponders, but not all
    - Re-routing is done with Aerobahn – start out side of taxi way. Have been using system for about three years
    - IAH ramp probably uses http://www.saabsensis.com/products/aerobahn/ in TaxiView
    - Ramp does not have access to ADSE-X (active system) which is made by the same company
- ERAM (En-Route Automation Modernization) prints strips
    - http://www.faa.gov/air_traffic/technology/eram/
    - http://en.wikipedia.org/wiki/ERAM
    - Houston Center inputs reroute
        - ERAM shows Houston center the planes in the air and their direction
    - Goes over ERAM system
    - New strip prints in tower
    - Clearance talks to pilot
    - Pilot confirms re-route
    - Pilot gets ready to taxi
    - Ramp confirms re-route with pilot
    - Pilot calls ramp when ready to taxi
- GateView

- Web based
- Ops send gate flow (print out of GateView)
  - If any changes, ops will communicate (phone calls)
    - Users of GateView can also see change visually
  - Gate flow is good for four hours and then prints a new one
- Information displayed
  - Inbound flight #
  - Outbound flight #Where airplane is coming from and going to
  - Organized by gate (each row is a gate)
  - Color represents the different types of aircrafts
  - Shows gate activity such as parked at gate, off gate but not off ground
  - Length of "puck" shows how long the plane is at the gate
- Only gate managers can make changes to gates
  - Gate managers have a special view on gate view to make changes
- Shows arrivals in 15 minute buckets
- Zone controllers get a pop-up when a change has been made
- Ramp controller usage:
  - Who's coming in?
  - Who's on the gate? Is the gate available?

- Chat system
  - Ramp controllers use a chat system to communicate between the two ramp controller towers
- Surface Movement Guidance and Control System (SMGCS) – pronounced "SMIGS"
  - http://www.gofir.com/aviation_accident_prevention_program/runway_safety_program/html/surface_movement_guidance_system.htm
  - In order to enhance taxiing capabilities in low visibility conditions and reduce the potential for runway incursions, improvements have been made in signage, lighting, and markings. In addition to these improvements, Advisory Circular (AC) 120-57, Surface Movement Guidance and Control System, more commonly known as SMGCS (acronym pronounced 'SMIGS'), requires a low visibility taxi plan for any airport which has takeoff or landing operations with less than 1,200 feet runway visual range (RVR) visibility conditions. This plan affects both air crew and vehicle operators. Taxi routes to and from the SMGCS runway must be designated and displayed on a SMGCS Low Visibility Taxi Route chart



Runway/Taxiway Arrangement Of SMGCS Features

Feature	Description
Stop Bar Lights	Row of red, in-pavement lights that when illuminated designate a runway hold position. ***NEVER CROSS AN ILLUMINATED RED STOP BAR.***
Runway Guard Lights	Elevated or in-pavement yellow flashing lights installed at runway holding positions.
Taxiway Centerline Lights	Green in-pavement lights to assist taxiing aircraft in darkness and in low visibility conditions.
Clearance Bar Lights	In-pavement yellow lights. When installed with geographic position markings they indicate designated aircraft or vehicle hold points.
Geographic Position Marking (pink spot)	Indicates a specific location on the airport surface.
Taxiway Centerline Marking	Provides a visual cue to permit taxiing along a designated path. Marking may be enhanced on light-colored pavement by outlining with a black border.

- Tugs
  - Maintenance is every 250 hours
  - At 1,000 hours, have a week long maintenance check known as D-check
  - Manufacturer is Douglas
  - Two different types:
    - Push back
    - Towing
      - Cradle closes on nose gear and provides complete control of the plane
  - 1 tug for every 2 gates

Personnel:

- Ramp controllers
  - East and west ramp controllers are in one tower
    - East ramp controller position is the most difficult due to the complexity of the traffic
  - North ramp controller is in another tower
  - Different qualifications for each position
  - 9 months to 1 year for certification
  - Role:
    - Says where to tow to (which letter)
    - Always listening for gate manager
- Tug team (push back of live flights)
  - 2 wing walkers/observers
    - Install chalks to the main gear
  - Driver - communicates with pilot
  - Computer tells the tug team

        - Team is assigned a tug for a day
        - Assigned as a driver/observer for the day
        - Computer program will tell task, flight and gate
    - Team composition changes daily and monthly
        - Every Monday, work with Tom and Mary
        - Every Tuesday, work with Jerry and Ken and etc.
        - Then that daily schedule changes each month
- Ramp lead
    - Each gate has a ramp lead who communicates with ops via radio, ex: gate changes
- Tow team
    - One wing walker/observer
    - One driver
    - Note: Tow 55 – 60 planes a day
- Tug driver qualifications
    - No safety violations in the last 15 months
    - No attendance violations in the last 15 months
    - Wide body qualified (777)
    - Narrow body qualified (73, 83, etc.)
    - Seniority order
    - 10 week training course
        - Learn about tugs, airport layout, signs for taxing, radio
- Exam at the end of each week, must score 90% or higher
    - Only for inbound flights
    - Use wands to guide airplanes into the gate and show them when to stop
    - Install noise gear and chalks
    - Provide the all clear for other ground operators to approach the plane
    - DFW have automated Marshalls aka Safe Gate
        - http://www.safegate.com/home/safegate-solutions/the-safegate-solutions/gate
        - https://www.youtube.com/watch?v=Mi8dDI8pz8k
        - First, ground crew selects the type of airplane that's coming in for the gate
        - Green light displays with arrows indicating move forward
        - After a certain threshold, the arrow changes to a number that counts down
        - Red light means stop
        - IAH is using Safegate at terminal D
- Operations personal
    - Sets up planned gate flow: now is April so works out till July
    - Night personal loads next day's plan
    - Software makes fixes
    - Person checks software fixes and communicates changes
- Gate managers
    - Determines gate changes
        - Try's to leaves departures where assigned and change arrivals
    - Manages GateView and makes changes as go

    - Give gate changes to zone controllers
- Zone controllers
    - Zone controllers are in charge of a group of gates (about 8) and located on the ground, ramp level
    - Located on north side at north level
        - Tasks include:
            - Communication for the group of gates responsible for
            - Monitor flights (receives a pop-up when a change has been made)
- Dispatch Center
    - Located in Chicago for United (airline specific)
    - Sets up and gives options for flight plan
    - Pilot gets flight plan and prints out in cockpit
        - Pilot does not have to file the flight plan. This is automatically done for them.
    - Only at the gate, flight plan changes will get updated in the system
    - If flight plan changes while in air (wheels up), no logging/updating of flight plan
- Pilots
    - Pre-departure clearance from tower is in their system
- Tower (FAA)
    - Should communicate to ramp what runways are being used
    - Depending on flow will change how planes are getting to the runway
        - Issue: Not always communicated to ramp control

Other information:

- CDR: coded departure routes
    - Pilots can pull up CDR's in the cockpit
- Ramp area = non-movement area (Ramp control)
- Taxi ways = movement area (ATC – ground control)
    - At IAH there is a movement area (decommissioned taxi-ways next to the ramp area) that the ATC does not monitor and ramp monitors.
    - Transfer control point: Once ramp hands over to ATC, for plane to taxi for departure, then ATC is on the clock for that plane.
- Taxi states for the day visiting:
    - Average = 5:45 min
    - Min = 2:33 min
    - Max = 12:21 min
- De-icing
    - 12 planes/hr depart when de-icing is needed
        - Normal rate is 20-30 planes/hr
        - Planes have different icing times and there are different techniques that can be used for de-icing
            - Issue: Tug may not be able to be attached during the de-icing

Terms used by ramp control:

- Surface Awareness (instead of situational awareness)

Other airports:

- DFW does not have push back points (circled radio alphabet on the ramp surface) like IAH.
- DFW has a lot of parallel runways.

Points to consider:

- APU (If APU is inoperative an air start is required)
- Start engine at gate then drop
- Cross bleed
- Sometimes chops/blocks fall off of carts
- Supervisors go around looking for FOD (no schedule)
- How to deal with emergency aircrafts such as medical emergencies (ex: heart attack)?
- Rush hours are 9AM and 5PM
- DFW does not have drop off points
- Might have problems with the pilot union but pilots know to trust controllers.
- Need to define boundaries of control
    - Who has control at what times
    - When can one make changes to the tug routes
- De-icing fluids (see additional notes above on de-icing)

Suggestions:

- When asked about who should have control of the tugs, the ramp controller responded that he prefers speaking to the pilot. Also would prefer the pilot to control the tug and be able to tell it to stop.
- Segmented planning for tugs will be helpful during rush hour
    - Need to have the ability to make adjustments to tug to keep traffic moving

Questions/need clarifications:

- Zone controllers and ramp leads are the same?

IAH Ramp Control Tour

Date of tour: 03/14/2014

Attendance: Ronald Archer, Kerry McGuire, Mai Lee Chang, E. Vincent Cross II

- **ATC Roles**
    - Flight Dispatcher (1 - 2) – Creates the flight data strips and hands off to the ground controller. If 2, the second person would be handling the weather information

- Ground Controller (1 or more) – manages movement on the taxiways. Can be further divided based on layout to manage different areas of the airport Organizes the flight data strips and passes onto the local controller. ATC ground gives pilots detailed instructions
- Local Controller (1 or more) – manages the active runways. Can be further divided into departures and arrivals. When entering/crossing an active runway pilots must contact local control to get permission.
- Supervisor (1-2) – Decides air traffic flow. Collaborates with other supervisors at other ATC towers and also with ramp control
- Other – Additional personal can be plugged in to assist with task such as monitoring weather

- **ATC Tower Operations**
  - Flight plans are filed by the companies, modified by computer and printed to ATC Flight Controller.
  - Flight controller
    - Creates flight data strip and hands off to ground controller
  - Ground controller
    - Communicates with pilot upon entering taxi area, providing taxi instructions.
      - Will also inform pilot to contact flight control if there has been a change in flight plan
      - Some airports use color coded routes. These routes have specific taxi instructions
    - To maintain SA
      - Primary is visually observing the environment
      - Secondary are the data strips i.e. how they are organized
      - Followed by ASDE-X
    - At some point that aircraft's data strip is passed onto local. Passing data strips appears to vary based on the ground controller
  - Local controller
    - Uses the placement of data strips to inform takeoff order.
    - Provides instructions to pilots on entering an active runway
- **ATC Equipment (IAH specific)**

- ATC is using equipment from United help with weather
    - Uses transponder squawk code
    - Highlights re-routes
- Airport Surface Detection Equipment (ASDE-X)
    - https://www.faa.gov/air_traffic/technology/asde-x/Airport Surveillance Radar (ASR)
    - Can individualize
    - Red dash – closed to for reconstruction/closure
    - Yellow – restricted to certain size aircraft
- Traffic Situation Display (TSD)
- Integrated Terminal Weather System (ITWS)
    - http://www.faa.gov/air_traffic/technology/itws/
- Terminal Radar Approach Control (TRACON)
    - http://www.faa.gov/about/office_org/headquarters_offices/ato/tracon/Information Data System (IDS) – like google
- Instrument Landing System (ILS)
    - "radio beam transmitter that provides a direction for approaching aircraft that tune their receiver to the ILS frequency. It provides both lateral and a vertical signals. It is a ground-based instrument approach system that provides precision guidance to an aircraft approaching and landing on a runway, using a combination of radio signals and, in many cases, high-intensity lighting arrays to enable a safe landing during instrument meteorological conditions (IMC), such as low ceilings or reduced visibility due to fog, rain, or blowing snow." – source Wikipedia (2/26/14)
- Digital (D-ATIS)
    - "continuous broadcast of recorded *non-control* aeronautical information in busier terminal (i.e. airport) areas. ATIS broadcasts contain essential information, such as weather information, which runways are active, available approaches, and any other information required by the pilots, such as important NOTAMs. Pilots usually listen to an available ATIS broadcast before contacting the local control unit, in order to reduce the controllers' workload and relieve frequency congestion. The recording is updated in fixed intervals or when there is a significant change in the information, like a change in the active runway. It is given a letter designation (e.g. *bravo*), from the ICAO spelling alphabet. The letter progresses down the alphabet with every update and starts at Alpha after a break in service of 12 hours or more. When contacting the local control unit, a pilot will indicate he/she has "information" and the ATIS identification letter to let the controller know

that the pilot is up to date with all current information.” – source Wikipedia (2/26/14)

9.2. Appendix B: Flow of information within the AOA when using SAFETug