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Purdue University

Department of Aviation Technology

Dual Image Grooved Sign (DIGS)

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COVER PAGE

Title of Design: Dual Image Grooved Sign

Design Challenge addressed: Runway Safety/Runway Incursions/Runway Excursions

University name: Purdue University

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Number of Undergraduates: 1

Number of Graduates: 1

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1. EXECUTIVE SUMMARY

This design packet addresses the Runway Safety Challenge of the FAA Design Competition for Universities in the 2011-2012 academic year. Our team's thorough research, review of current airport surface signage systems, and interaction with industry professionals contributed to our design solution for runway safety. The design is titled Dual Image Grooved Sign (DIGS). DIGS, embedded into the pavement, is designed to display two information signs when viewed from different angles, extending the system's use in two directions in relatively the same amount of area that a runway or taxiway pavement sign would occupy. As designed, in ground DIGS pavement signs will be placed in taxiways, providing the same ground guidance information such as TERM or taxiway J. A pair of DIGS will be placed on a taxiway, one on each side of the centerline, increasing the pilot's ability to determine his or her location on the airport. This will increase pilot awareness on the airside, reducing runway incursions. Ultimately, runway safety improvement will produce cost savings throughout the aviation industry and save lives.

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2. PROBLEM STATEMENT AND BACKGROUND

A recurring and prevalent problem within the aviation industry has been runway safety. With 954 runway incursions occurring in 2011, it is an issue that cannot be thrown to the way side (FAA, 2012c). While 2011 showed a slight improvement from 2010 (955 incursions), consequences of even one mistake in aviation can be unacceptably high (FAA, 2011b). Runway safety incidents costing approximately $100 million annually in the United States, and at their lowest consequence result in a ripple effect of delays at airports. Runway safety needs to be addressed, and the number of incursions needs to drop (Honeywell, 2009) if we are to maintain safety amidst growing demand for air travel.

Many innovative ideas have been developed and implemented to improve runway safety. However, obstacles are still in the way for a nationwide roll-out and implementation. One such idea is runway status lights (RWSL). RWSL is a novel and dynamic system to improve runway safety, by alerting pilots when a runway is in use. However, it has been sparsely installed due to high cost, with the most recent figures found for the installation of RWSL totaling $7.7 million at Los Angeles International Airport (Adams, 2008).

The Dual Image Grooved Sign (DIGS) design is believed to offer a quick, feasible and affordable solution to help combat the risks of runway incursions. It provides advantages to industry and addresses the recurring runway safety issues grappled with by industry for years.

The FAA has outlined the problematic areas of runway safety in various reports: the National Runway Safety Plan (NSRP) 2012-2014 and the FAA's Runway Safety Call to Action. In the NSRP, the FAA determined the most frequent runway incursion is attributed to Pilot Deviations, accounting for 65% of all incursions (FAA, 2011b). Within the Call to Action, the

FAA outlines initiatives to improve runway safety. Upgrading airport markings was highlighted as one of these initiatives (FAA, 2009a). The NTSB also has identified runway safety as a major problem within aviation by including it on their "2012 Most Wanted List," (NTSB, 2012). In addition, the Department of Transportation's Inspector General has identified improved markings and signage at airports as a critical area on which the industry should focus (DOT, 2008). DIGS was designed to align with the government's initiatives and goals, seeking to improve upon existing pavement signs installed at airports.

Specifically, DIGS seeks to better the pilot's situational awareness, which is defined as, "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future," (Garland et al., 1999). DIGS improves situational awareness during airport surface operations by enhancing the early perception critical information in the context of a busy and potentially confusing environment. According to the *Handbook of Aviation Human Factors,* situational awareness errors account for 71% of all accidents. 72% of these accidents were due to the failure to correctly identify information in the environment, including the problem of poor runway and taxiway markings and lighting (Garland et al., 1999). DIGS addresses this problem by instituting improved and additional ground markings that are readily seen from the flight deck. As an additional notification, when an aircraft taxis over DIGS, the grooves will cause a slight vibration. This will act as a secondary way to alert and remind the pilots to verify their location on the airport. By providing a new method to notify and inform pilots of their location on the airport, DIGS will decrease pilot deviations and increase their situational awareness through improved sign and instruction visibility.

3. LITERATURE REVIEW

3.1. Lenticular printing

Lenticular printing is a technology used to give the illusion of depth and morphing effect to 2D image. This technology was one of considered for use in our DIGS design. The technology can also display different information when viewed from different vertical viewing angle. Unlike DIGS, lenticular printing must be made of a sheet of transparent material, which is overlaid on the lenticular image. The transparent surface is made of a cylinder shaped lenticular lenses that reflects the image, and displays different image depending on the viewer's eye position. (Weiss & Pilossf, 2004)

Compared to the DIGS concept, lenticular printing does not have lateral viewing limits. However, while this capability may be desirable in other venues, it is not a suitable technology for the airport environment. Structurally, the amount of duress caused by the weight of an aircraft that the lenticular style lenses would have to withstand without damage has not been determined. For most applications, a transparent plastic is used to create the lenticular lenses. Conventional plastics cannot withstand heavy weight and high temperature conditions associated with an active airport environment when compared with concrete. Even if an alternative to transparent material were used, there is the risk that it may be scratched and rubber build-up may occur, obstructing the image. Furthermore, transparent materials may cause reflective glare, inhibiting and reducing the technology's usefulness during daytime hours. With those limitations and design considerations as a baseline, our team elected to focus on proven, pre-existing materials and to innovate literally "on top" of them.

3.2.MITRE 3-D painting

3-D painting was another technology researched. MITRE's 3-D paintings are actually painted two dimensionally, but it appears to be 3-D depending on the viewing angle. The example given by MITRE was a runway hold short line painted 3-D. When the hold short line is seen from the taxiway, the hold short line appears as 3-D like a wall. However, if the marking is viewed from the runway it appears just as a 2-D painting (MITRE, 2004).

This technology can benefit runway safety by increasing visual cues and therefore the pilot's situational awareness. Traditional runway hold short lines may not grab a fatigued and distressed pilot's attention. 3-D painting has a better chance of gaining a pilot's attention under high workload or fatigue conditions because pilots perceive the painting as a 3-D wall. The 3-D painting does not appear 3-D for pilots viewing the marking from the runways, so pilots do not have to confront a 3-D wall while heading to the taxiway. Unlike DIGS dual imaging design, MITRE's technology only appears to be 3D and is not capable of displaying two different images or provides separate information in two opposite directions. However, MITRE's 3-D painting techniques could be adapted to augment the DIGS design to create 3-D effect of DIGS data images.

3.3.Advisory Circulars

Advisory Circular (AC) 150/5340-1K, Standards for airport Markings, was studied as a foundation for our design specifications. The goal of DIGS was to create a sign capable of replacing or enhancing current ground markings, without changing or inhibiting compliance with existing FAA standards. In order to comply with FAA's standards, the location and size of taxiway markings are all based upon ACs. This guidance provided other important information and context such as paint and additional airport marking requirements and FAA's goals in this area (FAA, 2010b).

AC 150/5370-17, airside use of heated pavement was reviewed for pavement heating standards and current technologies. This particular AC helped the team's design approach for taking pavement heating technologies into consideration to meet heated pavement standards (FAA, 2011a).

4. PROBLEM SOLVING APPROACH

4.1. Design Overview

The Dual Image Grooved Sign (DIGS) design consists of an embedded, grooved concrete surface sign that displays two images when viewed from different angles (Figure 1). This dual surface signage is achieved by grinding and grooving a defined section of the concrete surface, then overlaying the surface with differing airport markings on either side of the grooves. The grooves will be in successive rows on the surface and angled, ideally at 45 degrees but could be changed to achieve best viewing angle. The grooves are angled to enable image visualization from a distance. The grooves will be triangular with a flat edge in between each groove. The tops of the grooves will also be flattened as opposed to converging to a point, increasing the structural resistance, to wear and tear from vehicle traffic. The groove design can be seen in Figure 1.

On each of the A sides of the grooves, a graphic will be placed, displaying the desired information. The same concept is applied to the B sides of the grooves, but with different information. This design allows for dual use information display depending on the approach direction. Figure 2 shows one example of airport signage that could be overlaid onto the grooves. The graphic will be divided in strips as shown in Figure 2.

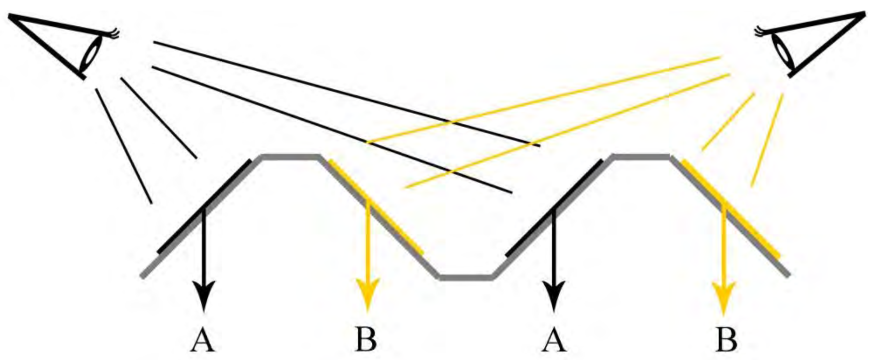


Figure 1 Basic Concept of DIGS

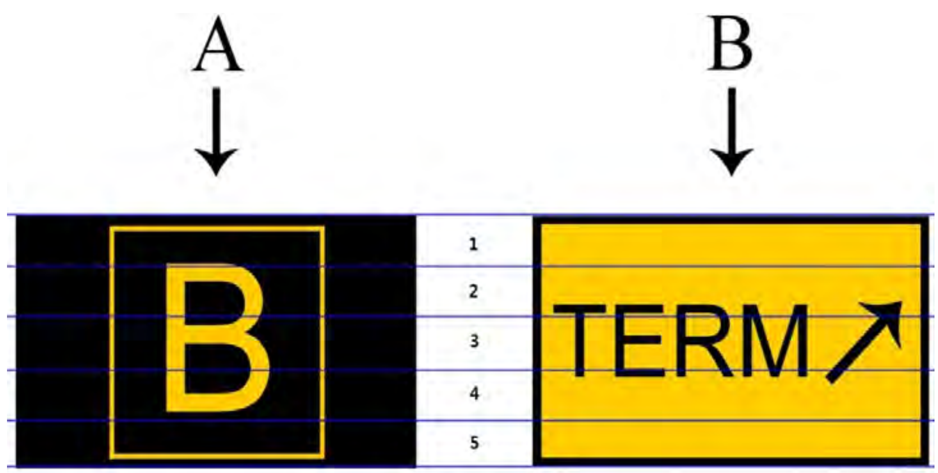


Figure 2

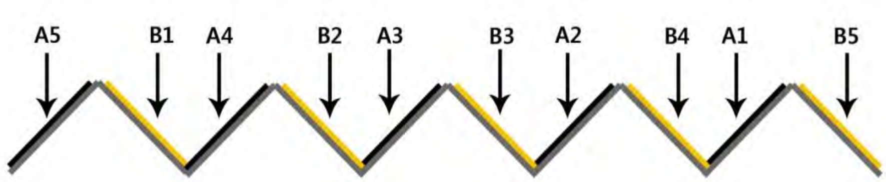


Figure 3 Sided view of DIGS

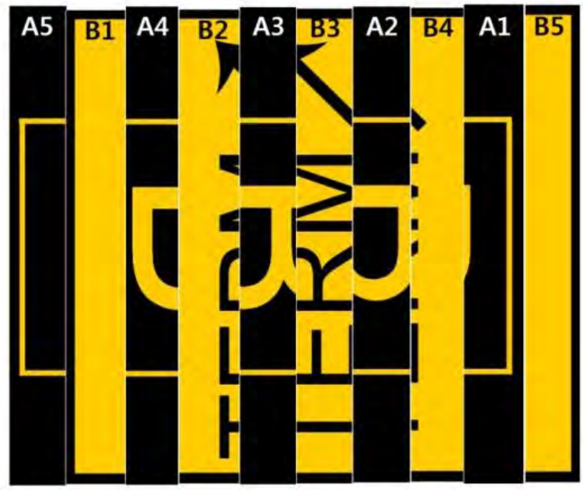


Figure 4 Aerial view of DIGS

The corresponding strip number is placed in order on a side of a groove as seen in Figure 3. This will achieve a congruent picture of the graphic when viewed from an elevated position. Figure 4 depicts the sign if it was viewed from above.

DIGS will be used to enhance pre-existing taxiway signs such as taxiway location signs, direction signs, and geographic position markings. DIGS will show different markings to two opposite directions. Airport operators can choose which information is given to what position, unlike traditional markings displaying same information when viewed from all sides.

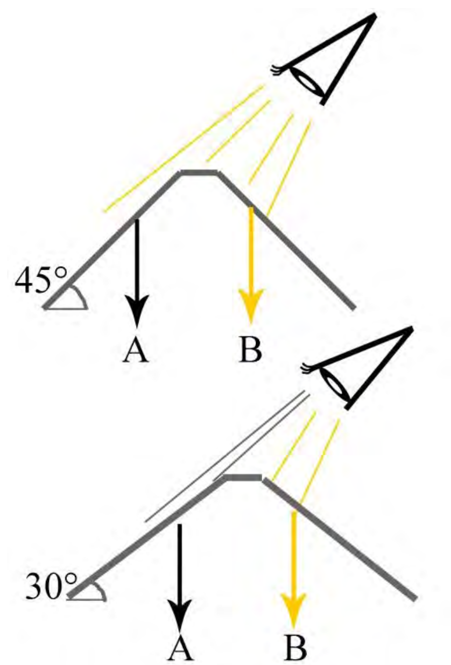


Figure 5 Angle demonstration

4.2.Design Specification

Groove Design

Each groove for DIGS has an angle of 45 degrees.

Although DIGS can utilize different angles to display information, 45 degree is best angle for signage usage. As shown in Figure 5, when a person is looking from a 45 degree angle, the person will only see the images on side B. However, if the groove is angled at 30 degrees, the person can see both sides (A and B on figure 5) of the grooves when he or she is looking from a 45 degree angle. Also, a higher sloped angle reduces chance of undesired materials accumulating over the markings. A slope higher than 45 degrees will experience lighting problems from a self-casted shadow.

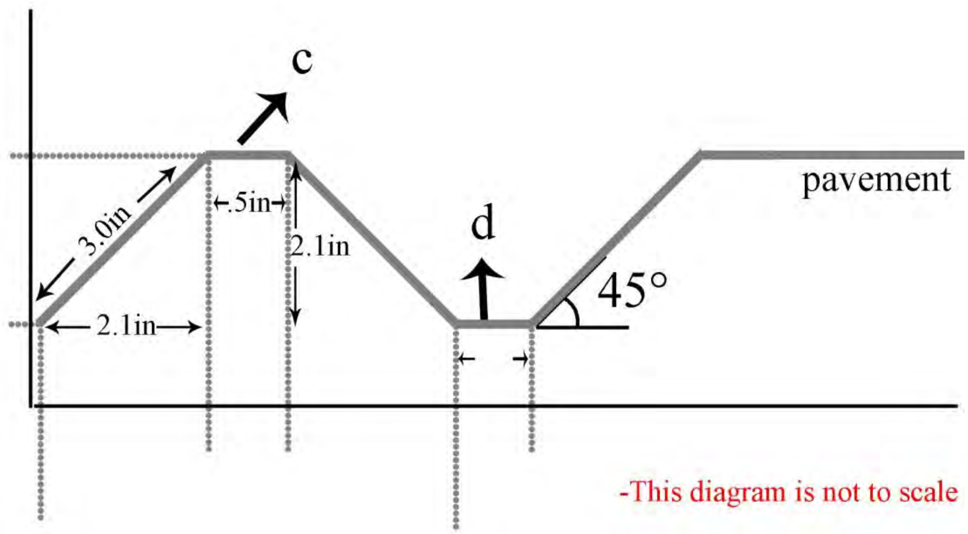


Figure 6 DIGS specification

The height of the groove is 2.1 inches. Each groove has two 3 inch sloped surfaces. The height of 2.1 inches was chosen to balance the engineering challenges of the manufacturing difficulty of small grooves and the amount of wheel drop an aircraft experiences, calculated on pg. 21-22. The markings will be painted on the sloped surfaces. The flattop and bottom gap, listed as c and d on Figure 6, is .5 inches wide. The flattop, c on Figure 6, is designed to increase the top surface area to reduce overall pressure to each groove. If a pointed edge is used instead of a flattop, the pointed edge will be easily damaged by friction and pressure. The bottom of the groove, d on Figure 6, is .5 inches. It has been designed to drain water during rainy and snowy conditions.

DIGS will be positioned at heavy traffic areas of airports. Due to the high stress environment, ultra-high strength concrete with 150 megapascal endurance is recommended to construct DIGS (Shah & Weiss, 1998). According to Dr. Stewart Shreckengast and Dr. W. Jason Weiss, the use of ultra high strength concrete will increase the life span of DIGS.

Groove Markings

All markings will be painted according to Advisory Circular 150/5340-1K (FAA, 2010b). Color, size, characteristics and font will be the same as pre-existing ground markings. For example, a DIGS taxiway location sign will have the same yellow 12 ft inscription with a black background. Although a 9 ft inscription height is the minimum for taxiway markings, 12 ft is recommended in order to embed more grooves for a larger area for the markings. The type of paint recommended for DIGS is epoxy based paint because of its durability. Glass beads would be included in paint used for DIGS to increase visibility of the marking during low visibility conditions.

4.3. Installation

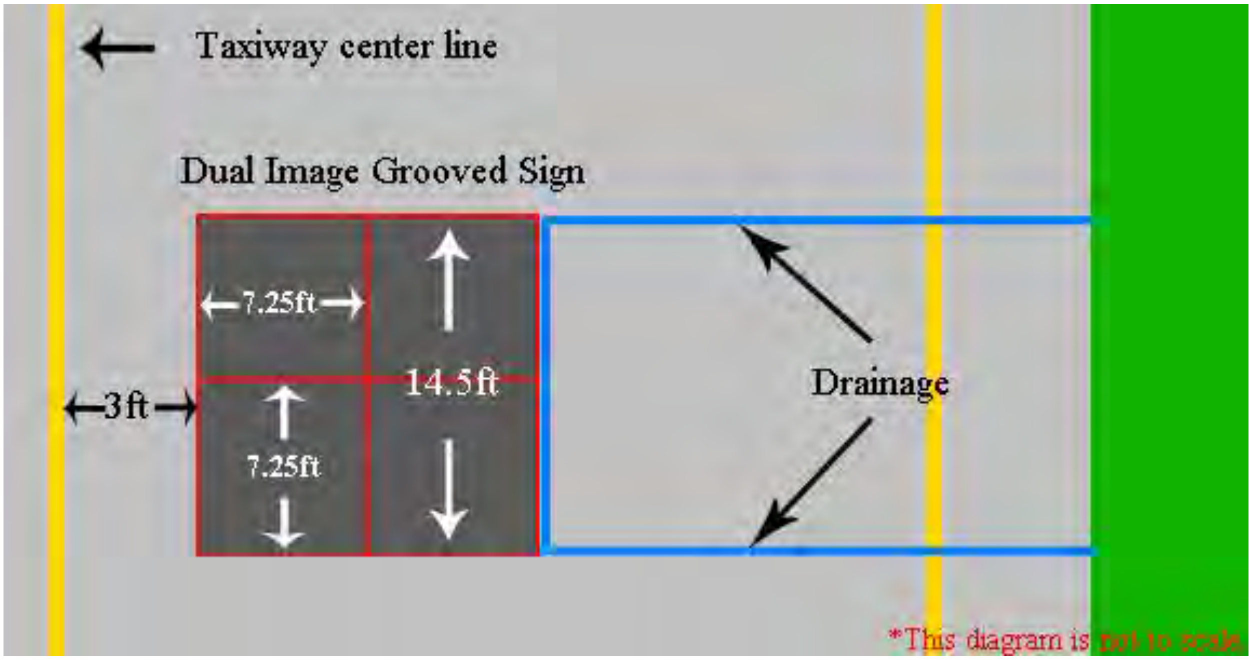


Figure 7 DIGS Installation

To comply with current FAA advisory circulars, DIGS will be installed 3 ft away from the taxiway centerline. To install the DIGS, part of the taxiway pavement will be cut into squares or rectangular shapes. The size of cutout will be different for the type and required size of the taxiway sign. A DIGS will consist of four square modules, each 7.4 x 7.4 ft and constructed from ultra-high strength concrete with 17 grooves as specified on pg. 13. For example, to install a taxiway location sign, a 14.8 x 14.8 ft square of pavement is required to be removed to install four DIGS modules as shown in Figure 7. For taxiway direction signs with arrows or surface painted holding position signs on taxiways, additional DIGS modules are required to match the specified size, and the pavement needs to be cut to match the size of the modules. Our prototype, Figure 9 on pg. 18, provides a realistic example of what a DIGS module would look like. Gaps between the DIGS modules and the pavement surface (red line shown on figure 7) would be filled with a joint sealant similar to the sealants installed between concrete joints at airports today. This would help reduce any drainage issues and vibration damages from vehicle traffic.

The modular installation method was selected to reduce overall time required for installations. Unlike grooving surface with a machine, the modules can be mass produced to decrease the manufacturing cost, and ensure uniform quality of each module. If DIGS instead used pre-existing pavement, which would be grooved to meet the DIGS design, there would not be uniform quality throughout the piece of pavement. Additionally it was determined that if one groove were to spall or become damaged, the entire DIGS unit might need to be replaced. By using four modules, only one part of DIGS would require replacement if damaged, therefore reducing maintenance costs.

To prevent water and snow accumulation, the DIGS unit would need to be crested to allow for drainage. To help facilitate the drainage, water drain grooves would need to be installed in addition to DIGS. If pre-existing taxiway grooves are as deep as 2.1 inches, additional water drain would not be required. To install the water drains, a traditional pavement cutter or grooving machine would be used. In the DIGS design, a water collection groove is embedded on the nearest side to the edge of the taxiway to collect water from each groove. The water would then flow to groove drains. Each water drain groove would be required to have a depth of 2.1 inches and be connected between the DIGS modules and sides of the taxiway shown as blue lines on figure 7.

4.4. Optional Features

DIGS is designed to endure all weather conditions. For airports that experience severe snow during winter, heated pavement would be required for DIGS. Due to the incorporation of grooves in DIGS' design, the grooves could be heavily damaged by snow plows. Furthermore, snow removal brushes and brooms can only be used when snow depth is below 0.5 inches, making the use of this evolution of the DIGS design potentially unsuitable in areas with heavy snowfall. Heated pavement would solve this problem by melting snow that accumulates between each groove, then draining to sides of the pavement. To reduce installation difficulty and heating source problems, the electronic heating method is recommended instead of the hydronic heating method. A grid of insulated conducting mesh would be recommended to be installed under each DIGS module to provide heat. It is also highly recommended to install a heating cable under the water drain grooves.

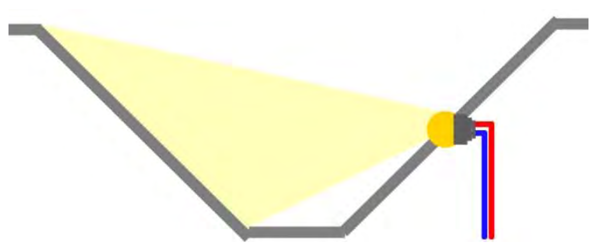


Figure 8 Lighting concept for DIGS

Unlike traditional ground markings, DIGS has the option of featuring lighting. High intensity LED lights may be embedded on each slope to light the opposing slope, depicted in Figure 8. High intensity LED lights are replaceable, smaller than traditional light bulbs, cheaper to operate and have a longer lifespan.

4.5. Operational Considerations

The most important operational consideration for DIGS is whether pilots can see the images on the sign. All aircraft have limited viewing angles for pilots due to cockpit window configurations. If the angle of an image is not properly configured, the cockpit crew cannot recognize the information displayed on DIGS. There are limited vertical and lateral viewing angles for DIGS. Further evaluation on the effects of vibration when aircraft taxi over the grooves at various speeds would be included in further development of the DIGS concept.

4.5.1. Vertical Viewing Angle

The vertical viewing angle is affected by the angle of groove. As mentioned on the groove design on pg. 13, using a low grooved angle would limit the visibility from steep angles. Although there is no limitation for the lower angles, research and experimentation on prototypes revealed that images can potentially be difficult to recognize at certain angle distances. A DIGS design with a higher number of smaller grooves on the same area (similar to resolution on a video screen) can display a better image for lower vertical viewing angle due to less 'pixelation' or distortion of the image. However, due to time and prototype manufacturing limitations for this design study, the current number and size of grooves are limited, as listed on pg. 13. To test vertical viewing angle, we made a smaller prototype of the DIGS, shown in Figures 9, 10, and 11. It should be noted that the prototype shown in these figures is smaller and does not match proposed design dimensions but was initially developed for experimenting with visualization. For the actual product envisioned, more grooves will be used to display the same image, decreasing image distortion and improving image clarity compared to the prototype.

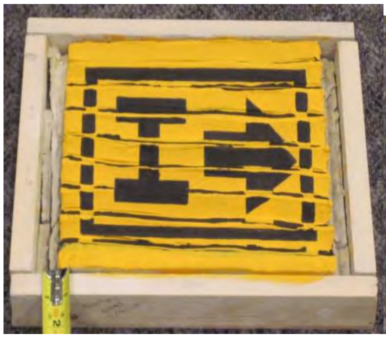


Figure 9 Viewing angle 45°

Figure 10 Viewing angle 30°

Figure 11 Viewing angle 15°

As depicted in Figures 8 to 10, DIGS can be recognized from different angles from 45 degrees to a shallow 15 degree downward viewing angle. The prototype was still recognizable even from 10 degrees. According to Boeing's ground maneuvering manual (Boeing, 2011a, b, & c), Boeing 737-800,747-400 and 777-200 each have viewing downward angles of 15, 18.5, and 21 degrees, respectively. These viewing angles are shown in Figure 12. Pilots of all modern Boeing aircraft can locate and identify DIGS from the cockpit. The viewing angle of each airplane can be different depending on the pilot's seating height. Boeing uses a designed eye reference point to determine the viewing angle, but some pilots do not adjust their chairs according to the eye reference point. Further research is recommended to determine pilots' seating habits and how it will affect the performance of DIGS.

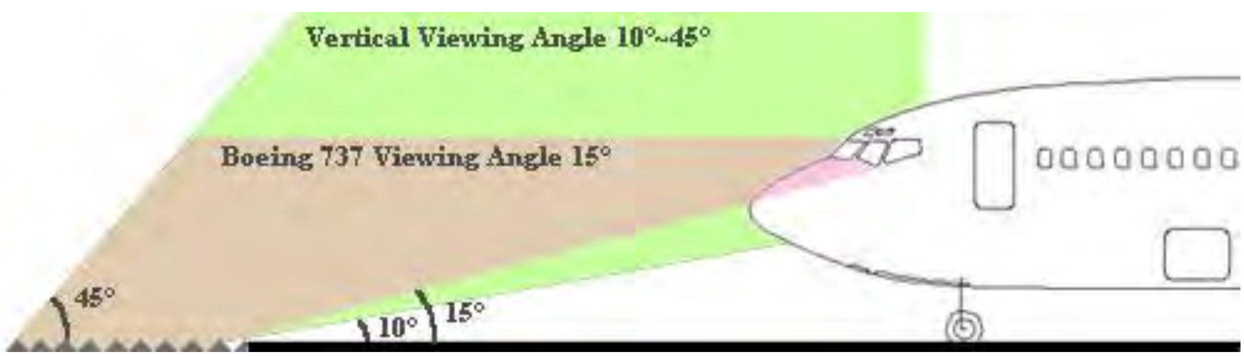
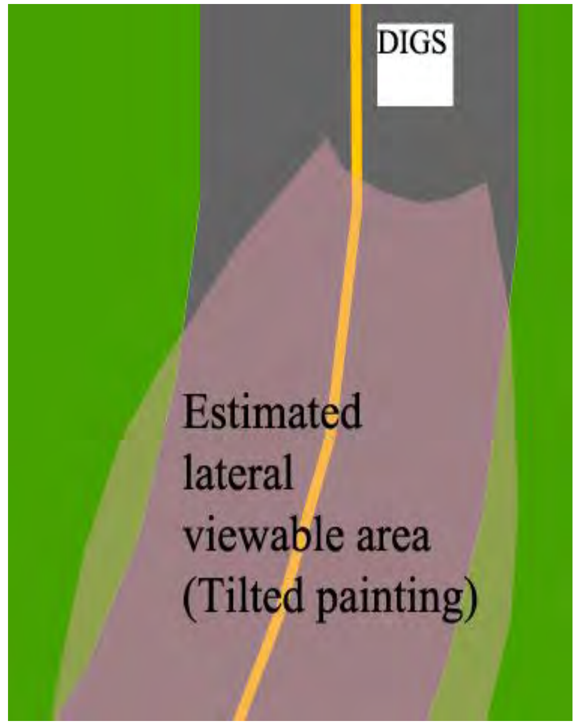


Figure 12 Boeing 737 Vertical Visual Angle

4.5.2. Lateral Viewing Angle

A lateral viewing angle is determined by width of the marking itself, and the distance from which the marking is viewed. If pilot's eye position is out of lateral viewing limit of DIGS, the images on the slope will appear as discontinued lines. If pilot's view point is further away, the lateral viewing limits narrows, shown in Figure 13. The lateral viewing angle can be different for each person. To compute viewing angles, the equation for the angles requires more statistical research on the pilot's DIGS lateral angle recognition.

Additionally, by tilting the inscription, the direction of lateral viewing angle can be changed without tilting the groove itself. Tilted markings can be used on a curved taxiway as shown on Figure 14. Figure 15 on the next page shows how images are tilted on the slope. Figure 16 shows the difference between the tilted markings and regular DIGS marking. Furthermore, an inscription on a DIGS can be progressively tilted different to achieve better lateral viewing angle.



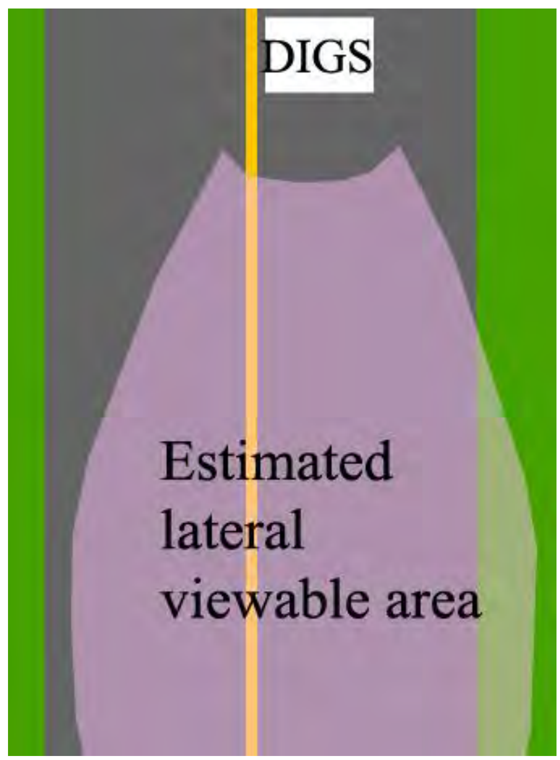


Figure 14 Estimated lateral viewable area of tilted inscription

Figure 15 Tilted inscription

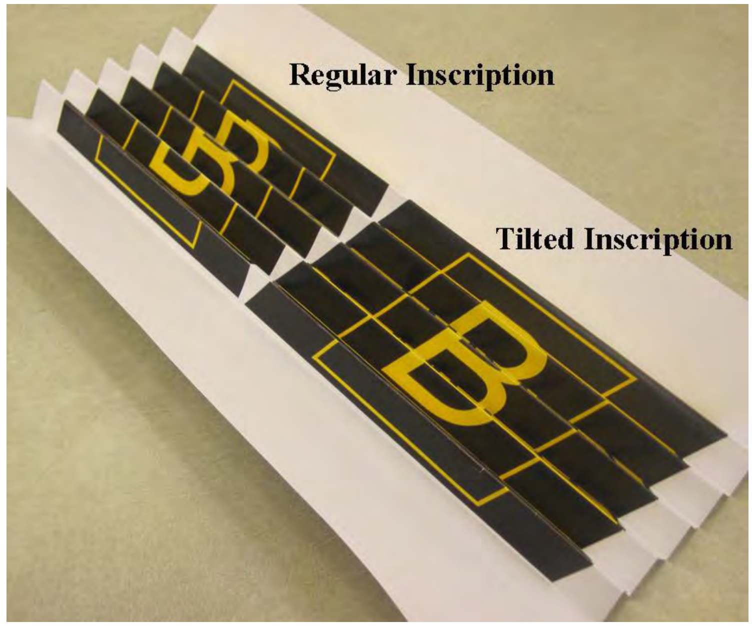


Figure 16 Inscription comparison

4.5.3. Wheel Drop (Vibration)

As aircraft tires move from the peak of the groove toward the bottom of the groove, the aircraft will experience a wheel drop. Continuous wheel drop and lift from the grooves will cause a vibration. While the duration of this vibration would be minimal, further evaluation would be required to assess potential cumulative wear to aircraft structure for both large and smaller General Aviation (GA) aircraft. Additional study of potential increase, decrease or zero effect on propeller strikes would also be required. To minimize the degree of vibration, the groove size could be reduced with additional design consideration given to the manufacturing process and groove endurance.

To calculate amount of wheel drop, we measured tire radius of a 5.00-5 size general aviation tire and retrieved dimension listings for a Boeing 737-800 tire radius from Boeing's website. B737-800's tire radius is 13.5 inches, and the radius of a Cessna 172’s 5.00-5 tires is 7 inches (Boeing, 2011a, p. 436). We used Equation 1 to calculate the amount of wheel drop that occurs with the groove specifications listed on pg. 13. Refer to Figure 17 for a graphical representation of the wheeldrop. Our calculation does not consider the deflation of the tire pressure.

Equation 1

Wheel Drop = Tire radius - Cos (Sin^{-1} (half the distance between the peaks/ tire radius))
5-500 tire wheel drop= 7 inches - Cos (Sin^{-1}(2.35inches/7inches)=0.4inches
Boeing 737-800 wheel drop = 13.5 inches - Cos (Sin^{-1}(2.35inches/13.5inches)=0.2inches

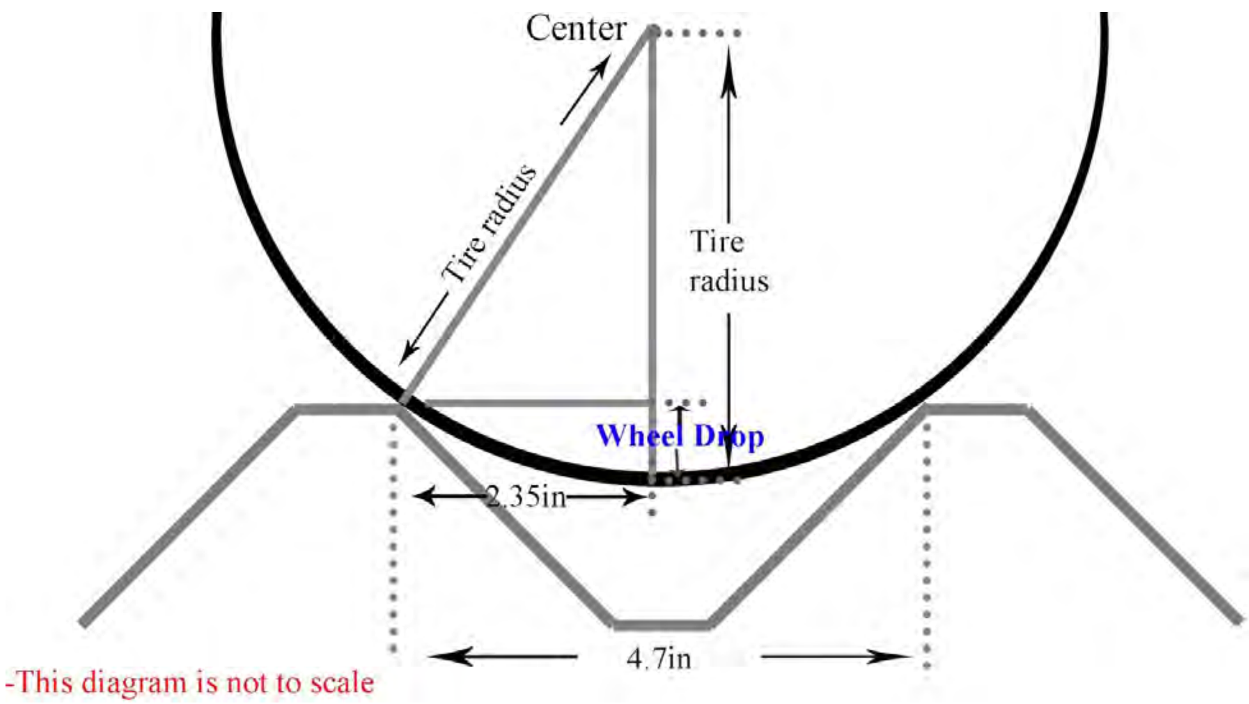


Figure 17 Wheel drop calculation

For a B737-800, the wheel drop is 0.2 inches. This wheel drop is not significant enough to cause damage to the airframe, but it may lead to slight passenger discomfort at a high speed. For GA aircraft using 5.00-5 tires, the wheel drop was 0.4 inches. Again, while this wheel drop may not be considered big, there is still the possibility for a propeller strike if the aircraft is taxiing at an excessively high speed. Overall, there are some safety concerns with GA aircraft, but the groove size allows for safe taxi when GA pilots operate at low speeds. If ultra-high strength concrete technology can create even smaller groove sizes, our specifications will be changed to reduce wheel drop and vibration.

5. SAFETY RISK ASSESSMENT

Referencing Advisory Circular 150/5200-37 (FAA, 2007), there were three Dual Image Grooved Sign's (DIGS) inherent risks that were identified and assessed. These are obstruction, human factors, and structural damage.

Severity / Likelihood	Minimal 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Frequent A		Obstruction			
Probable B					
Remote C					
Extremely Remote D			Propeller Strike	Pilot Error, Structural Damage	
Extremely Improbable E					

5.1.Obstructions

a. Hazard Identification- Since the painted grooves of DIGS are located below the surface level, there is high chance of rain, snow and Foreign Object Debris (FOD) accumulation. This accumulation can obstruct or change the information displayed on DIGS. Rain can reflect or refract the lights causing obstruction or misleading information. Snow can accumulate between the grooves blocking the markings. Lastly, FOD located between the grooves not only can obstruct the markings but can also cause damage to nearby moving aircraft.

b. Risk Assessment- Obstructions by rain, snow and FOD can occur often. Misleading information caused by these obstructions can lead to hazardous pilot confusion. Additionally, the FOD that is produced from DIGS can damage aircraft. Appropriate measures to monitor and inspect DIGS would need to be taken by airport operations staff.

c. Risk Treatment- As mentioned in the problem solving approach, the DIGS design includes cresting the pavement and installing water drains to remove any chance of rain accumulation. As with FOD, airports would be recommended to ensure the proper function of the drainage system of DIGS frequently in heavy rain and snow seasons. To prevent snow accumulation, airport managers can choose to install heated pavement below DIGS as described on pg. 16-17.

5.2.Propeller Strike

a. Hazard Identification- As mentioned on pg. 22, GA aircraft with 5-5.00 inch tires will have .4 inches of total wheel drop when the aircraft is traversing over DIGS. Although .4 inches of wheel drop is not significant enough to directly cause the prop strike, excessively high speed taxi can cause loss of control over DIGS. The vibration from high speed taxiing over the grooves can cause a resonance cascade of suspension leading to loss of balance of GA aircraft.

b. Risk Assessment- It is extremely remote to have a propeller strike of GA aircraft. Each GA aircraft has a larger propeller clearance than the actual wheel drop that is experienced when crossing the grooves. Also, most pilots taxi within safe speed limits, and it is very unlikely to find pilots taxiing too fast to cause the resonance cascade of the aircraft suspension. A propeller strike is categorized major for the severity of possible accident because it involves major injuries and damages to pilots and their aircraft.

c. Risk Treatment- To fix the safety gap, airport managers would need to implement awareness DIGS campaign with fixed base operators. Additionally, with help of the Aircraft Owners and Pilots Association (AOPA), we can educate GA pilots through AOPA's website. The awareness campaign would help pilots to recognize DIGS and taxi slower over it.

5.3.Pilot Error

a. Hazard Identification- Although DIGS is designed to reduce confusion and increase the efficiency of pavement markings, DIGS can create confusion when viewed from unintended angles. DIGS can only display recognizable information when viewed within its intended viewing angle. Pilots without prior experience of DIGS may misinterpret the unrecognizable graphic as valid information.

b. Risk Assessment- When a pilot misunderstands or becomes preoccupied with wrong information, he or she may cause major accidents such as runway incursion in the worst case scenario. However, this case is extremely remote to occur since all DIGS will be installed at specific locations, only visible within its intended viewing angles. The risk is also minimized by other taxiway signs around DIGS.

c. Risk Treatment- This human-error based risk can be solved by various methods. The simplest method is more training. Each pilot flying at an airport with DIGS installed, should be trained to use DIGS as supplemental information. This is because DIGS is intended to enhance the traditional signage not replace it. Airport diagrams should also include all the positions and orientation of DIGS.

5.4.Structural Damage

a. Hazard Identification- DIGS can become damaged from an extended period of wear and tear. The structural damage of DIGS can result in deformed marking and FOD created by the pavement cracking and breaking apart.

b. Risk Assessment- Although the possibility of significant structural failure is unlikely, the consequence of the failure is huge. FOD can damage airframes and engines, and deformed marking can confuse and disorient pilots.

c. Risk Treatment- Airport operators using DIGS would be required to inspect the sign for any cracks or damages to prevent development of FOD.

To minimize any other operational gaps, each airport implementing DIGS should create a new airport wide safety policy and training to minimize any risk. Airport management should also understand and identify the functions and risks of DIGS and promote SMS related education and training for the new signage.

6. INDUSTRY INTERACTION

After finalizing the major design paths of DIGS, the team consulted two pavement engineers, a former airline flight operations executive, an international aviation expert, and an airport operator. Through the diversity of industry backgrounds represented, the team sought a broad, collective view from each part of the industry. Each of these contacts provided vital feedback to our design, without which significant questions and gaps would remain.

6.1.John Haddock and Jason Weiss

Our first contacts were Purdue University Civil Engineering Professors John Haddock and Jason Weiss. Haddock's background is primarily in pavement design, with over 20 years in the industry. Aside from teaching pavement design courses, he instructs a graduate course in airport design and has a private pilot license. Professor Weiss is heavily involved with pavement research, having spent over 15 years in research and academia. His primary interests include concrete design, fractures mechanics, and development of ultra-high strength concrete.

Haddock's first concern was the possibility of standing water or snow in the grooves. In order to prevent standing water, we concluded to crest DIGS, which will cause the water to flow along the grooves to the edge where it will drain. To combat snow piling up and causing DIGS to no longer be visible, a heating wire will be placed in the bottom of the groove. The wire will melt the snow, with the water draining to the edges of taxiway.

His other issue with our design was the ability for the grooves to maintain their shape. He suggested utilizing concrete for DIGS due to its longer lifespan when compared to asphalt. However, he still had concerns about the concrete spalling and causing FOD to be present on taxiways. When DIGS is implemented at airports, we would suggest a more rigorous inspection of DIGS pavement to ensure no cracking or spalling.

As stated earlier, our design would divide the pavement sign into four square modules, allowing for easier installation and replacement of damaged pavement. Therefore, instead of replacing an entire DIGS, the airport can just replace one part, reducing maintenance costs. Haddock agreed with this idea and concurred that it would make the design more feasible and lower cost.

He provided the DIGS team with vital cost estimates for the project. Professor Weiss agreed with our use of ultra-high strength concrete for DIGS, in order to reduce maintenance costs and occurrence of FOD. While this concrete is more expensive than conventional concrete, it would only be installed in 219 sq. ft area, therefore not drastically increasing pavement costs. He recommended using the price of $60/sq. yard (or $26.67/sq. ft) for the cost of ultra-high strength concrete, with approximately a cost $1/sq. ft to grind and groove the concrete to our design. His total concrete design and installation estimate came out to $27.67/sq. ft, including cost of labor.

6.2.Stewart Schreckengast

Our next contact was Stewart Schreckengast, an aviation technology professor at Purdue University and former MITRE and ICAO airport consultant. He agreed with how DIGS can improve runway safety by increasing the situational awareness of pilots on taxiways. Also, he pressed our research team to quantify the decrease in runway incursions as a result of DIGS being implemented. He suggested focusing on utilizing DIGS at airports runway "hot spots," and reasoned that by engaging the most troublesome areas on airports, DIGS can have the greatest impact possible. Lastly, he believed the idea of dividing DIGS into a four modules was a strong solution to ensuring maintenance costs stay low.

Schreckengast did have a criticism of DIGS. Snow and ice accumulation in DIGS was a problem he saw in our design because the usage of snow plows on DIGS could cause a reduction in the lifetime of the groove. He agreed with our decision to include heating wires in the grooves to melt snow and ice. He also suggested using DIGS in areas that do not have snowy or icy conditions to avoid the problem, until a solution without using snow plows could be made.

6.3.Michael Suckow

Our fourth contact was Professor Michael Suckow, assistant department head of flight operations at Purdue University. An industry veteran with more than 30 years of aviation experience, Suckow previously served as Vice President of Flight Operations for Air Midwest and as Vice President of System Operations Control for Mesa Airlines.

When describing the DIGS design to Suckow, his first concern was night time operations and how pilots would be able to see DIGS. He suggested including LED lights in the grooves, which would either be powered by accessing the airfield lighting power grid or installing solar panels to provide electricity. We thought of the risk of installing solar panels in the safety area and agreed that it would be difficult to supersede FARs. Therefore, we concluded it would be easiest to power the lights via the airfield lighting power grid. When describing the minimal wheel drop that would occur when aircraft traversed DIGS, he suggested we calculate the probability of general aviation aircraft propeller strikes and scraping of the wheel skirts. We have taken this into account and determined neither of these are concerns, due to the fact that an average general aviation aircraft would have 0.4 inch wheel drop. This would not be sufficient for either a propeller strike wheel skirt strike.

Professor Suckow did believe that DIGS can improve runway safety, specifically pilot's situational awareness. To better the project feasibility and practicality, he recommended highlighting a troublesome area at an airport in order to show how DIGS could improve its runway safety. He also suggested installing DIGS before runway hold signs in order to notify pilots that they are entering a runway. He reasoned that this was where a majority of runway incursions and accidents occur.

6.4. Betty Stansbury

Our final contact was Betty Stansbury, director of Purdue University Airport and an Accredited Airport Executive. Ms. Stansbury has over 30 years of airport experience, from managing small, general aviation airports to large-hub international airports. She agreed with most aspects of the DIGS design. She had the same concern that Haddock and Schreckengast had with drainage and snow plows, but we have already addressed these concerns by cresting DIGS and installing heated wires in the grooves.

7. PROJECT IMPACT

As stated earlier, DIGS will provide cost savings to the aviation industry by reducing runway incursions and resulting costly accidents and delays. As part of the cost benefit assessment, the following questions were laid out: What is the estimated installation cost for a pair of DIGS? What are the projected annual maintenance costs? At what point will DIGS break-even? This section will address each of these questions to show the project's feasibility and practicality.

Concrete Costs	
Total sq. ft	219.04
Concrete $/sq. ft	$26.67
Grooving & grinding $/sq. ft	$1.00
Concrete cost/sq. ft	$27.67
Concrete cost/DIGS	$6,060.84

Table 1

7.1.DIGS Costs

The cost of concrete for a DIGS is listed in Table 1. Each DIGS covers approximately 219.04 square feet. The prices of ultra-high strength concrete and grinding/grooving of the concrete were estimated by one of our industry contacts and pavement engineer, Jason Weiss. The total estimated cost for the materials, installation and labor of the DIGS' concrete is $6,060.84.

Epoxy Paint Costs	
Number of grooves	34
Painted surface/ groove (ft)	0.5
Width/groove (ft)	14.8
Painted surface area (sq. ft)	251.6
Epoxy paint $/sq. ft	$1.50
Epoxy paint concrete/DIGS	$377.40

Table 2

In Table 2, the epoxy paint costs are broken down. As listed in the design specifications on pg. 13, there are 34 grooves per DIGS. The only areas of DIGS that will be painted are the slopes. This keeps the amount of epoxy paint required for each DIGS low. The total painted surface area was determined by multiplying the painted surface area per groove set (0.5 ft) by the width of a DIGS (14.8 ft), equaling 251.6 ft. The epoxy paint price/sq. ft was estimated from a Colorado Department of Transportation report on Concrete Epoxy Paint, which assessed the cost at $0.80/sq. ft, including labor (Goldbaum, 2010). We inflated the price due to the complexity in applying the paint to only parts of pavement. The total price for epoxy paint per DIGS, including labor, is estimated to be $377.40. Maintenance is major issue for pavement on an airport, which has been categorized and calculated in Table 3. In our design, we are seeking to reduce the maintenance required on DIGS by creating shallower grooves and flattening the top of each groove, with the goal being to decrease the corrosion of each groove. To estimate the amount of maintenance required each year, we used the Boeing 737-800 as our design aircraft, since it is the most common commercial aircraft in use today. The tire width of one 737-800 tire is 14 inches (Boeing, 2011a). Since DIGS will be placed on both sides of the centerline, the main gear, with two tires, will cross it. Therefore, the amount of tire width that moves over DIGS is 28 inches or 2.33 feet. Multiplying gear tire width by the length of DIGS (14.8 ft), total area projected to be placed under higher stress was estimated to be 34.53 feet.

Maintenance Costs	
Tire width (ft)	2.33
Length of DIGS (ft)	14.8
High stress area from AC tires (ft)	34.53
Concrete cost/sq. ft	$ 27.67
Epoxy paint $/sq. ft	$ 1.50
Total maintenance $/sq. ft	$ 29.17
Annual total DIGS maintenance cost $/ year	$ 1,007.34

Table 3

Due to the high stress that this area will endure, it may need to be repaired. Estimated cost of concrete/sq. ft with labor and grooving is $27.67. By adding the price of epoxy paint/sq. ft ($1.50), the total maintenance cost/sq. ft is $29.17. This was multiplies by the high stress area (34.53 ft) to determine the annual total maintenance cost per year of $1007.34.

Total DIGS Costs	
Concrete cost/DIGS	$6,060.84
Epoxy paint concrete $/DIGS	$377.40
Total single DIGS cost	$6,438.24
Pair of DIGS cost	**$12,876.47**

Table 4

The total cost for a pair of DIGS (Table 4) is estimated at $12,876.47, which has been multiplied by two because our design calls for a DIGS on both sides of the taxiway centerline. Through conservative estimation, we expect a pair of DIGS to last 10 years and have annual maintenance costs of $2,014.68. Also, we forecast DIGS will not require maintenance until at least one year after installation. From this information and using a 2.5% annual inflation rate, we can determine the total project cost over its lifetime and what the project cost can be averaged out to per year. These costs are shown in Table 5.

Project Lifetime	
Cost	**Year**
$12,876.47	1
$2,014.68	2
$2,065.05	3
$2,116.67	4
$2,169.59	5
$2,223.83	6
$2,279.43	7
$2,336.41	8
$2,394.82	9
$2,454.69	10
$32,931.64	**project lifetime cost**
$3,293.16	**project cost/year**

Table 5

7.2. Cost Benefit from DIGS

As stated in Table 5, a pair of DIGS will cost $32,931.64 to install and maintain over its 10 year life span. In 2009, Honeywell has estimated that runway incursions cost commercial airlines approximately $100 million annually. Utilizing the most recent runway incursion numbers and cost published by Honeywell, 1009 in 2008, each runway incursion cost approximately $99,108.03. Because DIGS improves a pilot's situational awareness and about 71% of incursions are caused by lack of situational awareness, we project a reduction in the number of incursions (Garland et al., 1999). In Table 5, the average cost of DIGS per year was calculated to $3,293.16. Therefore, the net benefit of implementing DIGS is $95,814.86. However, this is assuming a runway incursion happens annually at an airport, when perhaps a more realistic estimate is that one runway incursion happens within a 10 year timeline. Using this scenario, the net benefit of implementing DIGS is $66,176.38.

7.3. Airport Example

To demonstrate the practicality of DIGS, we will provide an example of implementing our design at Phoenix Sky Harbor International Airport (PHX). The Western-Pacific Runway Safety Region has been the most problematic region for the FAA, accounting for more than a quarter of all runway incursions in the United States, with 243 in this region in 2011. We chose to initially implement DIGS in this region due to this factor. Also, by implementing DIGS in this warm-weather region, we no longer have to deal with the issue of snow removal from DIGS. When identifying which airport to implement DIGS, we researched FAA "hot spots," defined as a runway safety related problem area or intersection on an airport (FAA, 2009b). The FAA has identified a hot spot at PHX at the south end of Taxiway F. This has been particularly troublesome to pilots because they confuse Taxiway F for one of two runways located on either side of this taxiway (FAA, 2012a). Figure 18 shows the existing pavement markings at PHX, which has a total of 12 markings in this small area. Pilots can easily become confused from this and misread a sign, possibly leading to a runway incursion. By using

Figure 18 Satellite view of PHX hot spot 1 (Google, 2012)

DIGS, four of these signs will be replaced by two signs. These two replacement signs, the DIGS, will only display two information signs as opposed to four information signs, when approaching from either runway. This is depicted in Figure 19. A simple replacement of traditional pavement signs with DIGS can drastically improve runway safety by allowing the pilot to understand his or her location on the airport.

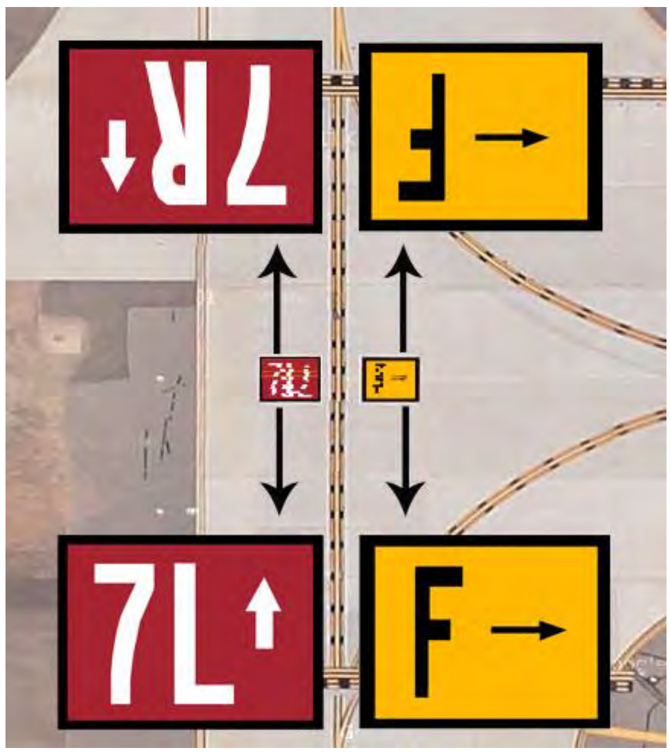


Figure 19 Hot spot 1 with DIGS implementation

Appendix A

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Appendix B

Purdue University is a coeducational, state-assisted system in Indiana. Founded in 1869 and named after benefactor John Purdue, Purdue is one of the nation's leading research institutions with a reputation for excellent and affordable education. Purdue University is accredited by the Higher Learning Commission of the North Central Association of Colleges and Schools. The West Lafayette campus offers more than 200 majors for undergraduates, over 70 master's and doctoral programs, and professional degrees in pharmacy and veterinary medicine. Purdue University's College of Technology is one of the largest and most renowned technology schools in the nation with more than 34,000 living alumni. More than 5,500 Purdue students are currently pursuing their education in the College of Technology. The College of Technology consists of eight academic departments, and resides in ten Indiana communities in addition to the West Lafayette campus. The Aviation Technology department is one of the eight departments within the College of Technology. Three undergraduate programs are offered within the department: Aeronautical Engineering Technology, Aviation Management, and Professional Flight. Graduate studies in Aviation Technology are also offered. In addition, the department pursues signature research areas that embrace tenets of the emerging Next Generation Air Transportation System, which include Hangar of the Future aircraft maintenance technology innovation, National Test Facility for Fuels and Propulsion, and Safety Management Systems.

Appendix C

The DIGS research team did not have a non-university partner during the project.

Appendix E

For student members:

1. Did the FAA Design Competition provide a meaningful learning experience for you? Why or why not?

The FAA Design Competition did provide a meaningful experience for our research team. Experiencing firsthand the problems that major airlines, airports and government officials encounter was eye-opening. The number of challenges and obstacles that these parties deal with daily has helped us understand how and why the industry it is today.

2. What challenges did you and/or your team encounter in undertaking the Competition? How did you overcome them?

Our greatest challenge was determining the cost and the benefit of the project. To overcome this challenge we reached out to professionals outside of aviation in order to gain a better understanding of pavement costs. The other challenge that our team had was time management and handling a project of this magnitude with team of only two students. We solved this problem by meeting weekly and utilized technology like Google Docs to update each other on the progress of the project. During the final two weeks, we met every other day to ensure project was completed on time.

3. Describe the process you or your team used for developing your hypothesis.

To first develop our problem background, we investigated the areas within aviation that needed drastic improvement. We saw that runway safety was major issue and to improve it, there needed to be a new, cost-effective design. Then, we collaborated with industry professionals to understand the main causes to the problem that we were addressing and to receive feedback on our design. Next, we took the industry's suggestions and looked at the areas that needed to be developed more. Lastly, we assessed the practicality of our design and whether or not the majority of the industry would find it useful.

4. Was participation by industry in the project appropriate, meaningful and useful? Why or why not?

Our interaction with industry professionals was vital to tailoring and adjusting our project to make it more feasible and realistic. We reached out to professionals outside of aviation in order to gain feedback on topics with which were not familiar. We believe that this was very appropriate, and we suggest that future participants in the competition do the same.

5. What did you learn? Did this project help you with skills and knowledge you need to be successful for entry in the workforce or to pursue further study? Why or why not?

We enhanced our research and critical thinking skills through identifying the research problem, assessing current practices, determining a solution, and defining the impact of project. By working with a smaller research group, we learned to always review each other's answers and conclusions. We believe these skills will be essential to our careers in aviation. Overall, it has been a very rewarding experience, and we recommend college students to participate in the competition.

For faculty members:

l. Describe the value of the educational experience for your student(s) participating in this competition submission.

This project had an innovation concept that stretched the students to pursue patent and existing technology identification during their literature/technology review. The team was forced to have continuous collaboration and diligence in fact finding as they developed their idea; this included meeting design challenges put forth by others to prove the viability of their idea and re-design.

2. Was the learning experience appropriate to the course level or context in which the competition was undertaken?

The student team's experience was salient and appropriate to the R&D within the Hangar of the Future laboratory at the University, and the type of innovation and problem solving being looked at within the Next Generation Air Transportation System in the air transportation industry. Students were able to utilize the Department's large aircraft and ramp area for visualization, prototype development and initial testing, which is exactly what our real world large aircraft laboratory is designed for. There was an excellent use of the aircraft, airframe lab and real airport workspace. As a team comprised of an undergraduate and graduate, this was an excellent example of moving from coursework knowledge to applied (hands-on) real-world application.

3. What challenges did the students face and overcome?

They discovered some preexisting design similarities forcing the team to critically evaluate their own ideas, what the true outcome of their design was to enable, and identify specific differences and improvements. They had to ask the critical 3rd and 4th questions like, "beyond just being a slick idea, WHO will it serve, HOW WELL compared to existing methodologies, how robust is the design and what MULTI-USE capabilities could there be?"

4. Would you use this Competition as an educational vehicle in the future? Why or why not?

Definitely would use this competition and the type of questions and research it drives. In fact this competition is a natural and relevant outlet to the style of education and problem solving I strive for in my Aeronautical Engineering Technology courses, which are heavy in applied knowledge, experimentation, literature and technology review and applications, immersive learning etc.

5. Are there changes to the Competition that you would suggest for future years?

Our concern is one that has been shared before however it is not all bad. That would be that it is nerve wracking to determine if the team's idea presented is not already in existence somewhere which was not discovered during the in the literature and technology reviews (was due diligence followed deeply enough for the time allotted?). I believe this is positive, in that it teaches the importance of deep research and the ethical decision making of acknowledging professionally others' previous work. Glad to see the addition of new topics and would encourage you to continue opening design ideas that incorporate cross-disciplinary collaboration between different operations (Ramp, Gate, Tower etc.).

Appendix F

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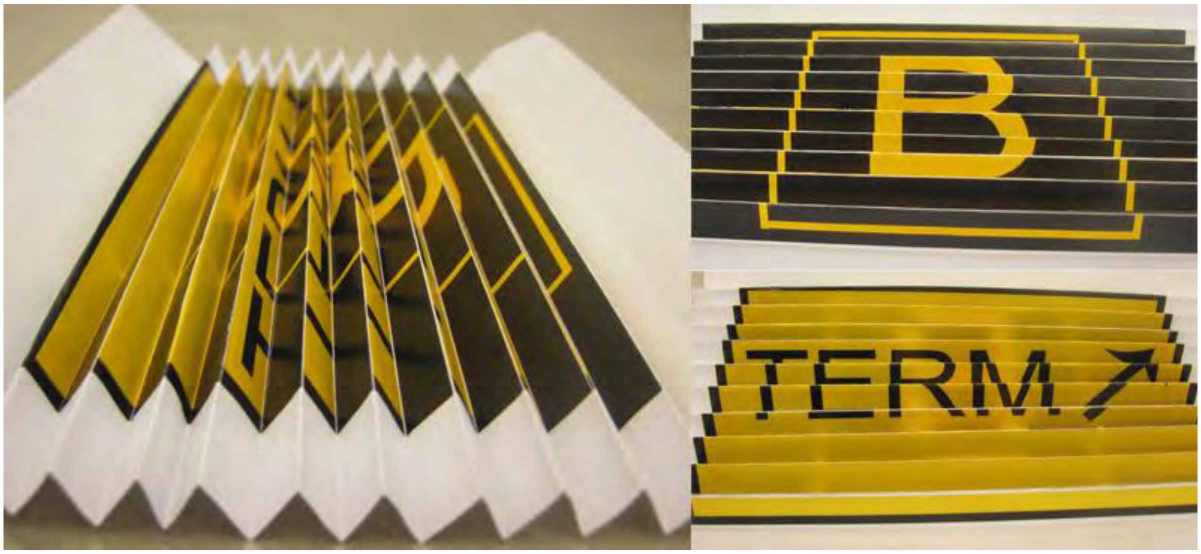
Appendix G- DIY DIGS



Please print out pg. 49 in color, and fold as shown above to create your own DIGS.