Investigation of an Autonomous Landing Sensor for Unmanned Aerial Systems

A Ram (Bella) Kim, Iowa State University
Investigation of an Autonomous Landing Sensor for Unmanned Aerial Systems

Julian McCafferty¹, Amir Bachelani², Bella Kim³, Graham Ray⁴, and Davis Woodward⁵

University of Kansas, Lawrence, KS, 66045

This research focused on characterizing the precision, reliability, sensitivity, and uncertainty of an autonomous landing sensor. Currently, the most dangerous flight phase for autonomous aircraft is the landing and takeoff segments, accounting for almost 70% of crashes. This research analyzes the effects of the color and roughness of the landing surface, fog, ice, and varying aircraft angles on the performance of an automated landing sensor. An investigation of suitable sensors was performed and the Dimetix FLS-C30 laser altimeter was selected for testing. The standard deviation and uncertainty of each condition was found and compared. It was determined that surface color, texture, and angles had a minimal effect on the repeatability of the laser altimeter, but that environmental hazards such as fog can potentially have a significant impact on performance. It is recommended that further accuracy and dynamic testing is performed.

Nomenclature

\[ UAS = \text{Unmanned Aerial System} \]
\[ UAV = \text{Unmanned Aerial Vehicle} \]

I. Introduction

TAKEOFF and landing pose the greatest threat to unmanned aerial systems (UAS) today. For decades autopilot systems have proven their reliability in aircraft navigation and control; however, humans are often required in the loop during takeoff and landing procedures. Unmanned aerial vehicles (UAV) such as the Pioneer (RQ-2) and Army Hunter (RQ-5) rely on an External Pilot (EP) standing next to the runway in visual contact with the aircraft during landing. In a study performed in 2004 by the U.S. Department of Transportation and the Federal Aviation Administration, 67% of mishaps due to human factors occurred during takeoff and landing for the RQ-2, and 78% for the RQ-5 (Ref 1). Meanwhile, the Army Shadow (RQ-7) uses an automated landing system for recovery called the Tactical Automated Landing System (TALS) and only reported 25% of accidents attributed to this system while negating human factors during landing. Many errors during landing by an EP are attributed to the difficulty of piloting from a reversed perspective to the aircraft as well as the lack of physical feedback from the aircraft on the pilot. The Air Force Predator drone (MQ-1 and MQ-9) provides pilots on the ground with a 30-degree field of view forward facing camera. This report attributed only 13% of human factor mishaps to landing error; however, 67% of all mishaps were reportedly due to human factors because of

¹ Undergraduate Student Lead, Department of Aerospace Engineering, 2120 Learned Hall 1539 W. 15th St.
² Undergraduate Student, Department of Aerospace Engineering, 2120 Learned Hall 1539 W. 15th St.
³ Undergraduate Student, Department of Aerospace Engineering, 2120 Learned Hall 1539 W. 15th St.
⁴ Undergraduate Student, Department of Aerospace Engineering, 2120 Learned Hall 1539 W. 15th St.
⁵ Undergraduate Student, Department of Aerospace Engineering, 2120 Learned Hall 1539 W. 15th St.

American Institute of Aeronautics and Astronautics
the great complexity and necessary training to operate the ground control station. A report by the US Air Force 311th Human Systems Wing on unmanned aerial vehicle mishaps noted that pilots had not developed the necessary skills to learn basic maneuvers and landing in the Predator until 150 – 200 hours of flight time. Furthermore, they reference a study in which 66.7% of Predator mishaps involving skill-based errors occurred during landing, and referenced a USAF Safety Center Predator Mishap Report in 2004 which recommended “automating the landing phase of flight to eliminate the need for proficiency in the landing skill set” (Ref 2). The Office of the Secretary of Defense report on UAV Reliability stated that “UAV reliability is important because it underlies their affordability, their mission availability, and their acceptance into civil airspace” (Ref 3). With high acquisition costs and training time to operate unmanned systems, the costs attributed to mishaps are detrimental to not only accomplishing their mission, but their acceptance and further development in the future. Compared to General Aviation with a single mishap per 100,000 flight hours, the RQ-2 Pioneer alone has recorded 334 mishaps per 100,000 hours (Ref 2). It is readily evident that UAS reliability is a significant issue and mitigating the risks of pilot error by developing repeatable automated takeoff and landing will drastically improve their longevity and future acceptance.

Current autonomous take-off and landing (ATOL) research revolves around the use of Global Positioning Satellite (GPS). In 2005 researchers from Stellenbosch University used a GPS to navigate an aircraft to the runway at which point an ultrasonic finder would be utilized to determine altitude. A similar system was again designed except a camera system was used to determine altitude instead of the ultrasonic finder. The most recent research currently involves the use of high-precision GPS measurements, which do not necessitate the need for additional altitude sensors, but instead need the heading and altitude measurements of the runway (Ref. 4).

After researching journals and documents, several sensors were selected as candidates for autonomous landing purposes. The first sensor was a GPS receiver. Boeing used GPS receivers for auto landings in their Integrity Beacon Landing System (IBLS). The IBLS consisted of two beacons placed near the landing touchdown zone and a GPS receiver on the aircraft that guided the aircraft to the landing zone. These tests were conducted in 10 knot cross winds, and landing was completed successfully 111 times without failure (Ref. 5). Researchers at the University of Oregon State in Corvallis, Oregon tested the vertical accuracy of GPS receivers and compared them to the claims made by the manufactures. In their testing, the receivers had a raw signal vertical accuracy of 2.7 meters with a standard deviation of 1.8 meters. However, the measured data was widely different from the manufactures data, which reported a vertical accuracy of 0.01 to 0.02 meters (Ref. 6).

Ultrasonic range finders were researched as a potential altimeter because of their low cost. However, the nature of the sensor limits its capability. Because the sensor sends out a conical ultrasonic signal, the range received might not be the range directly in front of or beneath the vehicle. Ultrasonic range finders also suffer because of differences in surface reflection and absorption of sound. These two factors will distort the information coming back to the sensor. Ultrasonic range finders are also limited by the speed of sound. This becomes important during collision avoidance when a fast signal is needed. In the article examined, ultrasonic range sensors were declared accurate to within 0.03 meters (Ref. 7). It should be noted that this is for ideal conditions on the ground.

The laser altimeter sensor has several limitations but proved to be a good candidate for use in an autonomous landing arrangement. These findings were investigated by a team at the University of Kansas. The sensor emits a laser that detects the reflection of the beam off of the ground. The time that the laser beam takes to return to the sensor is relative to the distance above the ground. If the vehicle is flying wings level, this could be used to find the height of

American Institute of Aeronautics and Astronautics
the UAV. To determine pitch or roll, two lasers must be used. Four lasers are necessary for simultaneous calculations of pitch, roll, and attitude. While successful in reporting the aircraft’s flight characteristics, the lasers used in this study only had a range of 1 to 10 meters (Ref. 8).

A full cost analysis was performed to select the most effective sensor for this application and the FLS-C30 distance measuring device was selected for testing. The precision, reliability, sensitivity, and uncertainty of this sensor are characterized for integration into an automated landing system. The Dimetix FLS-C30 laser altimeter is tested on various runway surfaces that a UAV may encounter on landing.

II. Theory

Laser rangefinders emit a laser pulse and then detect the reflection of that pulse off of the target object. To determine the range to the target, the time of flight of the pulse is calculated. The distance is calculated using time of flight and the speed of light.

The autonomous landing sensor must accurately detect above ground level altitude at all expected approach attitudes. In the case of a laser rangefinder, the distance output of the sensor varies with changes in pitch and roll. Figure 1 shows this effect assuming a laser rangefinder mounted along the z-body axis. The Euler angles of the aircraft must be considered to convert the sensor output to the correct altitude.

\[ w_x' = \sqrt{\left(\frac{\partial x'}{\partial x} w_{\text{meas}}\right)^2 + \left(\frac{\partial x'}{\partial \theta} w_{\text{manufacturing}}\right)^2} \]

Where:

\[ x' = \frac{x}{\cos \theta} \]

The variable \( x' \) considers the uncertainty in zeroing of the laser to the testing surface as well as the uncertainty in adjusting the angle on the testing apparatus. To calculate the values for \( w_{\text{meas}} \), which consists of the uncertainty of the sample size and the resolution uncertainty of the Dimetix FLS-C30 laser, Equation 3 was used.
The manufacturing uncertainty was measured as the uncertainty on the test rig itself. This accounts for error in the angle of the test stand in calculations.

III. Methodology

The following subsections will detail the testing apparatus and procedure used to conduct testing.

A. Apparatus

The apparatus consists of a testing stand with the attached sensor, and the rotating apparatus which holds the testing surface. This was selected due to its simplicity as well as the ability to measure a wide range of variables quickly. The following is a list of materials that were used:

- Tripod
- Dimetix FLS-C30 Laser Altimeter
- Bosch DRL 130 Laser Range Finder
- Scrap Wood
- Surfaces
  - Concrete
  - Asphalt
  - Grass
  - Black, Red and White Construction Paper
  - Ice
- LabVIEW software

A Dimetix FLS-C30 laser rangefinder was used in this experiment. The FLS-C30 features a visible targeting laser and an infrared laser for measurement purposes. The module dimensions of the FLS-C30 are 150 mm x 80 mm x 55 mm. The module weighs 1.52 lbs. The manufacturer claims the module's operating span is 0.5 to 65 meters on natural surfaces (up to 500 meters on highly reflective surfaces). Dimetix also claims +/- 3 mm accuracy of measurements at 20 Hz sample rate. The laser has both analog and digital outputs available. It operates on DC power with a voltage range of 9 to 30 volts (Ref. 9). Further specifications can be found in Reference 9.
A Bosch DLR 130 was used to determine the reference distance as seen in Figure 3. This measurement was used to align the surfaces to the distances needed for testing. The two laser sensors were combined as seen in Figure 4.
The test stand which holds the various surfaces and colored paper had to be manufactured. It consisted of a base board, a vertical member that rotated about a hinge, and a surface mounting board. A hinge was used to be able to rotate the surface easily. This hinge was mounted to a vertical member that held the surfaces. Screws were drilled into the surface board so that the concrete and asphalt pieces could be easily mounted and held in place. The completed test stand is shown in Figure 5. A bolt is dropped into holes drilled in 5 degree increments in the base plate once the stand is rotated to the desired angle. This allows for repeatability and removes the need to measure the angle of the test stand for each measurement.

Figure 4. Integration of the Tripod and Laser Altimeter

Figure 5. Testing Fixture
Different testing surfaces were prepared with the help of the civil engineering department at the University of Kansas. The civil engineering department donated the concrete and asphalt for this project. These materials were aged for approximately one year such that their properties and surfaces are consistent with operating runways exposed to weather. Black, red, and white paper was provided from the aerospace department at the University of Kansas. A small section of grass was removed from a section of the Learned lawn at KU, and ice was created by freezing water in a smooth surface container. The surfaces can be seen in Figure 6.

![Various Surfaces for Altimeter Testing](image1)

**Figure 6. Various Surfaces for Altimeter Testing**

Figure 7 shows the completed setup at the 0.5 foot distance with ice. This set up was replicated for each of the distance measurements. Additional testing was performed using the sublimation from dry ice to simulate fog and haze over the ice surface. The setup for this testing is shown in Figure 8.

![Ice Testing Apparatus](image2)

**Figure 7. Ice Testing Apparatus**
In addition, LabVIEW software was set up for measuring and recording the data. The LabVIEW code was designed so that statistical analysis was performed as the data was collected. Screenshots of the LabVIEW code can be found in the Appendix.

B. Procedure

With the prepared apparatus, the measurement of the distance for the various surfaces should be conducted as the following list.

1. Install the laser altimeter on the tripod.
2. Connect the cables for the laser altimeter and computer.
3. Adjust the tripod so that the laser can reach the desired surface.
4. Move the test stand to the desired distance.
5. Measure the distance from the laser to the surface with the DLR 130.
6. Adjust as necessary to achieve the correct distance.
7. Run LabVIEW software using a sample size of 20 measurements. Enter the reference distance in the specified box and click measure.
8. Change the surface and repeat Steps 5 - 8 until each surface has been tested at 30, 20, 10, 5, 2, 1, and 0.5 foot intervals.

The following list presents the procedure for measuring the angled surface.

1. Install the laser altimeter on the tripod.
2. Connect the cables for the laser altimeter and computer.
3. Adjust the tripod such that the laser can reach the desired surface.
4. Ensure the laser altimeter is level by adjusting the stand and reading the installed level device.
5. Install test stand at the desired distance.
6. Measure the distance from the laser to the surface with the DLR 130.
7. Adjust test stand to the desired angle.
8. Run LabVIEW software using a sample size of 20 measurements. Enter the reference distance and angle in the specified box and click measure.
9. Repeat Steps 5 - 8 until each angle has been tested.

Angle will vary 0, 5, 10, 15, 20, 25, and 30 degrees for each distance. The distance will vary same as the above. The angle procedure is only done for the black paper surface because this is deemed to be the least reflective surface.

Additional testing was performed to further augment the project’s findings. One is the distance measurement using ice as a surface. The other is the distance measurement with ice and sublimating dry ice over the surface to simulate a haze or fog. The procedure of the distance measurement of the ice surface is same as the first static test. The distance measurement in simulating haze is given as follows:

1. Repeat Steps 1-8 from the surface testing using ice as the surface.
2. Prepare the dry ice with warm water on the tray.
3. Run LabVIEW software using a sample size of 20 measurements. Enter the reference distance in the specified box and click measure.
4. Pour the warm water to the tray. If necessary, blow over the surface of the tray to direct the fog.
5. Repeat without the interference of the dry ice fog to establish a baseline.

This measurement is only performed at a distance of 10 ft because of limitations of the dry ice. The following procedure was used to perform an uncertainty analysis of a compound angle:

1. Install the laser altimeter on the tripod.
2. Connect the cables for the laser altimeter and computer.
3. Adjust the tripod so that the laser can reach the desired surface.
4. Ensure the laser altimeter is level by adjusting the stand and reading the installed level device.
5. Install the test stand at the desired distance.
6. Measure the distance from the laser to the surface with the DLR 130.
7. Adjust as necessary to achieve the correct distance.
8. Using a 30 degree triangle, use materials available to prop the bottom of the base such that the base is at the 30 degree angle of the triangle.
9. Run LabVIEW software using a sample size of 20 measurements. Enter the reference distance in the specified box and click measure.

IV. Results

The following subsections will detail the results obtained in testing.

A. Standard Deviation

For the surface testing the results in Table 1 were recorded. These denote the standard deviation of the measurements. A graphical representation of the results for the surface testing can be seen in Figure 9. For increased clarity the ice measurement was removed in Figure 10.
### Table 1. Standard Deviation for Surface Testing (in)

<table>
<thead>
<tr>
<th>Surface</th>
<th>30 ft</th>
<th>20 ft</th>
<th>10 ft</th>
<th>5 ft</th>
<th>2 ft</th>
<th>1 ft</th>
<th>0.5 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt</td>
<td>0.0175</td>
<td>0.0196</td>
<td>0.0502</td>
<td>0.0358</td>
<td>0.00993</td>
<td>0.00722</td>
<td>0.00973</td>
</tr>
<tr>
<td>Black</td>
<td>0.00817</td>
<td>0.00958</td>
<td>0.0107</td>
<td>0.0133</td>
<td>0.0121</td>
<td>0.0156</td>
<td>0.00737</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.00735</td>
<td>0.00694</td>
<td>0.00692</td>
<td>0.00277</td>
<td>0.00694</td>
<td>0.00550</td>
<td>0.00687</td>
</tr>
<tr>
<td>Grass</td>
<td>0.0106</td>
<td>0.0106</td>
<td>0.00884</td>
<td>0.0228</td>
<td>0.0101</td>
<td>0.0140</td>
<td>0.0555</td>
</tr>
<tr>
<td>Red</td>
<td>0.00576</td>
<td>0.00783</td>
<td>0.00518</td>
<td>0.00470</td>
<td>0.0104</td>
<td>0.00561</td>
<td>0.00721</td>
</tr>
<tr>
<td>White</td>
<td>0.00739</td>
<td>0.00589</td>
<td>0.00589</td>
<td>0.00653</td>
<td>0.00674</td>
<td>0.00820</td>
<td>0.00629</td>
</tr>
<tr>
<td>Ice</td>
<td>0.0321</td>
<td>0.0256</td>
<td>0.0820</td>
<td>0.246</td>
<td>0.279</td>
<td>0.152</td>
<td>0.00735</td>
</tr>
</tbody>
</table>

**Figure 9. Standard Deviation for Surface Testing**

**Figure 10. Standard Deviation for Surface Testing without Ice**
For the angle testing the results in Table 2 were recorded. These denote the standard deviation of the measurements. A graphical representation of the results for the surface testing can be seen in Figure 11.

<table>
<thead>
<tr>
<th>Angle</th>
<th>30 ft</th>
<th>20 ft</th>
<th>10 ft</th>
<th>5 ft</th>
<th>2 ft</th>
<th>1 ft</th>
<th>0.5 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00817</td>
<td>0.00958</td>
<td>0.0107</td>
<td>0.0133</td>
<td>0.0121</td>
<td>0.0152</td>
<td>0.00737</td>
</tr>
<tr>
<td>5</td>
<td>0.00510</td>
<td>0.00967</td>
<td>0.00453</td>
<td>0.00592</td>
<td>0.00656</td>
<td>0.00632</td>
<td>0.00671</td>
</tr>
<tr>
<td>10</td>
<td>0.0109</td>
<td>0.00755</td>
<td>0.00619</td>
<td>0.00558</td>
<td>0.00932</td>
<td>0.00777</td>
<td>0.00592</td>
</tr>
<tr>
<td>15</td>
<td>0.00933</td>
<td>0.00771</td>
<td>0.00465</td>
<td>0.00677</td>
<td>0.00648</td>
<td>0.00968</td>
<td>0.0103</td>
</tr>
<tr>
<td>20</td>
<td>0.00946</td>
<td>0.00813</td>
<td>0.00470</td>
<td>0.00503</td>
<td>0.00739</td>
<td>0.00814</td>
<td>0.00630</td>
</tr>
<tr>
<td>25</td>
<td>0.0110</td>
<td>0.00671</td>
<td>0.00717</td>
<td>0.00968</td>
<td>0.00674</td>
<td>0.00654</td>
<td>0.00951</td>
</tr>
<tr>
<td>30</td>
<td>0.00983</td>
<td>0.00634</td>
<td>0.00488</td>
<td>0.00940</td>
<td>0.00827</td>
<td>0.00780</td>
<td>0.00851</td>
</tr>
</tbody>
</table>

![Figure 11. Standard Deviation for Angle Testing](image)

Additional testing was performed to simulate fog. Table 3 shows the difference between ice testing and the ice testing with fog. This can be seen graphically in Figure 12.

<table>
<thead>
<tr>
<th>Type</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice</td>
<td>0.0286</td>
</tr>
<tr>
<td>Ice With Fog</td>
<td>0.595</td>
</tr>
</tbody>
</table>

Table 3. Ice Standard Deviation
Another additional test performed was using a combined angle. This would simulate a combined pitch and roll. The comparison between the single angle and combined angle testing can be seen in Table 4. This is shown graphically in Figure 13.

Table 4. Compound Angle Testing Standard Deviation

<table>
<thead>
<tr>
<th>Type</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Angle</td>
<td>0.00983</td>
</tr>
<tr>
<td>Combined Angle</td>
<td>0.0123</td>
</tr>
</tbody>
</table>

Figure 13. Combined Angle Standard Deviation Difference at 30 ft
B. Uncertainty

To perform the uncertainty analysis, baseline errors were found which can be seen in Table 5. Using these uncertainties and the uncertainty equation, as well as the distance measurement, the total combined uncertainty can be found in Table 6 and Table 7 for the surface and angle testing respectively. Graphical representations for the total uncertainty are given in Figure 14 and Figure 15.

Table 5. Baseline Uncertainties

<table>
<thead>
<tr>
<th></th>
<th>Resolution Uncertainty</th>
<th>Manufacturing Uncertainty</th>
<th>Zeroing Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.004</td>
<td>3 deg</td>
<td>3 deg</td>
</tr>
</tbody>
</table>

Table 6. Total Combined Uncertainties for Surface Testing

<table>
<thead>
<tr>
<th>Surface</th>
<th>30 ft</th>
<th>20 ft</th>
<th>10 ft</th>
<th>5 ft</th>
<th>2 ft</th>
<th>1 ft</th>
<th>0.5 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt</td>
<td>0.844</td>
<td>0.559</td>
<td>0.281</td>
<td>0.140</td>
<td>0.0546</td>
<td>0.0265</td>
<td>0.0129</td>
</tr>
<tr>
<td>Black</td>
<td>0.844</td>
<td>0.561</td>
<td>0.282</td>
<td>0.141</td>
<td>0.0557</td>
<td>0.0278</td>
<td>0.0145</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.8444</td>
<td>0.561</td>
<td>0.282</td>
<td>0.141</td>
<td>0.0561</td>
<td>0.0281</td>
<td>0.0146</td>
</tr>
<tr>
<td>Grass</td>
<td>0.8394</td>
<td>0.553</td>
<td>0.278</td>
<td>0.136</td>
<td>0.0517</td>
<td>0.0221</td>
<td>0.0155</td>
</tr>
<tr>
<td>Red</td>
<td>0.844</td>
<td>0.560</td>
<td>0.282</td>
<td>0.141</td>
<td>0.0558</td>
<td>0.0280</td>
<td>0.0144</td>
</tr>
<tr>
<td>White</td>
<td>0.844</td>
<td>0.561</td>
<td>0.282</td>
<td>0.141</td>
<td>0.0559</td>
<td>0.0280</td>
<td>0.0144</td>
</tr>
<tr>
<td>Ice</td>
<td>0.831</td>
<td>0.559</td>
<td>0.272</td>
<td>0.143</td>
<td>0.0789</td>
<td>0.0463</td>
<td>0.0187</td>
</tr>
</tbody>
</table>

Table 7. Total Combined Uncertainty for Angle Testing

<table>
<thead>
<tr>
<th>Angle</th>
<th>30 ft</th>
<th>20 ft</th>
<th>10 ft</th>
<th>5 ft</th>
<th>2 ft</th>
<th>1 ft</th>
<th>0.5 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.844</td>
<td>0.561</td>
<td>0.282</td>
<td>0.141</td>
<td>0.0557</td>
<td>0.0278</td>
<td>0.0145</td>
</tr>
<tr>
<td>5</td>
<td>0.842</td>
<td>0.565</td>
<td>0.281</td>
<td>0.139</td>
<td>0.0570</td>
<td>0.0281</td>
<td>0.0155</td>
</tr>
<tr>
<td>10</td>
<td>0.842</td>
<td>0.565</td>
<td>0.281</td>
<td>0.138</td>
<td>0.0571</td>
<td>0.0283</td>
<td>0.0166</td>
</tr>
<tr>
<td>15</td>
<td>0.842</td>
<td>0.565</td>
<td>0.280</td>
<td>0.138</td>
<td>0.0571</td>
<td>0.0284</td>
<td>0.0155</td>
</tr>
<tr>
<td>20</td>
<td>0.842</td>
<td>0.565</td>
<td>0.280</td>
<td>0.138</td>
<td>0.0573</td>
<td>0.0285</td>
<td>0.0151</td>
</tr>
<tr>
<td>25</td>
<td>0.842</td>
<td>0.565</td>
<td>0.279</td>
<td>0.138</td>
<td>0.0573</td>
<td>0.0285</td>
<td>0.0149</td>
</tr>
<tr>
<td>30</td>
<td>0.842</td>
<td>0.565</td>
<td>0.278</td>
<td>0.138</td>
<td>0.0573</td>
<td>0.0284</td>
<td>0.0141</td>
</tr>
</tbody>
</table>
To further help make the data useful, the percent total uncertainty was used. The total uncertainty was divided by the measurement distance. This can be seen in Table 8 and Table 9 as well as a graphical representation in Figure 16 and Figure 17. To help clarity, the last value of grass and ice was removed from Figure 16 and is shown in Figure 18.

**Table 8. Percentage of Total Combined Uncertainty for Surface Testing**

<table>
<thead>
<tr>
<th>Surface</th>
<th>30 ft</th>
<th>20 ft</th>
<th>10 ft</th>
<th>5 ft</th>
<th>2 ft</th>
<th>1 ft</th>
<th>0.5 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.235</td>
<td>0.237</td>
<td>0.251</td>
</tr>
<tr>
<td>Black</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.235</td>
<td>0.238</td>
<td>0.246</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.235</td>
<td>0.237</td>
<td>0.245</td>
</tr>
<tr>
<td>Grass</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.235</td>
<td>0.241</td>
<td>0.467</td>
</tr>
<tr>
<td>Red</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.235</td>
<td>0.237</td>
<td>0.246</td>
</tr>
<tr>
<td>White</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.235</td>
<td>0.237</td>
<td>0.245</td>
</tr>
<tr>
<td>Ice</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.256</td>
<td>0.406</td>
<td>0.361</td>
<td>0.241</td>
</tr>
</tbody>
</table>
Table 9. Percentage of Total Combined Uncertainty for Angle Testing

<table>
<thead>
<tr>
<th>Angle</th>
<th>30 ft</th>
<th>20 ft</th>
<th>10 ft</th>
<th>5 ft</th>
<th>2 ft</th>
<th>1 ft</th>
<th>0.5 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.235</td>
<td>0.238</td>
<td>0.246</td>
</tr>
<tr>
<td>5</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.237</td>
<td>0.244</td>
</tr>
<tr>
<td>10</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.237</td>
<td>0.261</td>
</tr>
<tr>
<td>15</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.235</td>
<td>0.237</td>
<td>0.246</td>
</tr>
<tr>
<td>20</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.235</td>
<td>0.237</td>
<td>0.244</td>
</tr>
<tr>
<td>25</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.235</td>
<td>0.237</td>
<td>0.246</td>
</tr>
<tr>
<td>30</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.234</td>
<td>0.235</td>
<td>0.237</td>
<td>0.247</td>
</tr>
</tbody>
</table>

Figure 16. Percentage of Total Combined Uncertainty for Surface Testing

Figure 17. Percentage of Total Combined Uncertainty for Angle Testing
The sensor demonstrates a high level of precision based on these results. The standard deviation varies slightly from surface to surface, but with differences that are within hundredths of an inch. This could be attributed to random fluctuations as much as a difference in how the sensor reacts to different surfaces.

Only two anomalies from the standard deviation of Figure 10 were seen. The largest came from the testing on the asphalt at 10 and 5 ft. The cause of the error is not fully understood; however, one variable that can be discounted is the emissivity of the black asphalt because it had no effect on the data. This is known, because of the testing that was done on the black construction paper which shows no high standard deviation compared to the other surfaces. The error may have occurred because of the rough surface of the asphalt test specimen. This would effectively alter the measurement if the laser were to reflect from a porous surface on the test material.

The other anomaly occurred when testing grass at lower distances. The error for this test is better understood. The grass specimen that was chosen was 4 inches tall. When the testing was done at the 0.5 foot distance the blades were nearly touching the laser altimeter. The laser would have a greater chance of reflecting off of a blade of grass, because of the close proximity.

One surface the sensor did not deal well with was the ice as shown in Figure 9. Although the maximum standard deviation is only around a quarter of an inch, it is the largest standard deviation seen in the data. The sensor had difficulty in detecting the ice. It appeared during the testing that the visible laser was penetrating the front of the ice and reading a point somewhere inside of the ice. This can be attributed to the translucency of the ice. This is a significant result, but likely not a concern because translucent ice is not commonly seen in a snowy runway. The ice that was tested was simply frozen water which is much more translucent than packed snow or ice seen in an arctic environment.

Figure 12 shows that the ice testing with the haze included caused a much higher standard deviation than the other cases of approximately 0.6 inches. This standard deviation is still highly precise and plenty adequate for an autonomous UAV landing, but significant enough that it should be addressed when designing an autonomous landing methodology.
For the angle testing there again was no discernible pattern as shown in Figure 11. It appears from these graphs that random error and noise account for the fluctuation. Even with this fluctuation the standard deviation remains low.

Since it was assumed the baseline errors were the same for each test, the only variable between surfaces and angles was the sample size uncertainty. This contributes a very small portion to the overall total uncertainty so there was little difference. Overall, the standard deviation of any of the tests was very small and errors can be attributed to faulty surfaces or noise and random fluctuations in the measurement.

VI. Conclusion

Testing was performed across a distance of 30 ft and at angles ranging from 0 to 30 degrees for various surface color and roughness. Further testing was performed at combined angles and for ice and fog. The results of these static precision tests indicate that the Dimetix FLS-C 30 exhibits a very high level of precision under nearly all tested conditions which is adequate for use during autonomous landing. It is highly effective at measuring altitude over a variety of potential runway surfaces, colors, and angle under static ideal conditions. Angle of laser incidence has minimal effect on the laser’s precision and the levels of uncertainty across all surfaces and angles remained close to constant. Adding multiple angles such as pitch and roll from an aircraft have very little effect to the sensor’s precision. Concerns arise when measuring distance from a translucent surface such as clear ice and under foggy conditions when haze may interfere with the laser’s signal, although the sensor still performs well with minor interference. If the altimeter would ever have to perform under these unlikely circumstances, further testing would be required.

The authors recommend that the Dimetix FLS-C 30 sensor undergo the following further testing:
- Accuracy testing
- Dynamic state testing (including both horizontal and vertical translation)
- Flight Testing

This project successfully characterized the repeatability of the altimeter sensor; However, accuracy testing with similar conditions in this project is recommended to verify the manufacturer’s claims of +/- 3 mm in ideal conditions. Dynamic testing is recommended to properly verify the laser altimeter’s performance in a dynamic environment. This sensor’s typical application is for industrial environments such as trains and cranes. This likely means that the altimeter would perform well dynamically, but it should still be tested before being flown. Finally, a proper flight test would demonstrate the laser’s performance in flight which is always recommended for a comprehensive review of a sensor’s capabilities.

Appendix

Screenshots of the LabVIEW code are displayed in Figure 19 through Figure 21.
Figure 19. LabVIEW Software Block Diagram

Figure 20. LabVIEW Software Front Panel

American Institute of Aeronautics and Astronautics
Acknowledgments

The authors would like to acknowledge the assistance of Matt Brown, the Aerospace Instrumentation Class Graduate Teaching Assistant, for his help in LabVIEW programming and suggestions for testing. We would also like to acknowledge the Aerospace Engineering Department at the University of Kansas for funding the laser altimeter sensor and Dr. Shawn Keshmiri for providing the opportunity and experience to conduct this research.

References


Figure 21. LabVIEW Chauvenet's Criterion Sub VI