University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Project Definition Document (PDD)

Vehicle-Based Infrastructure Analysis (V.I.A.) LiDAR System

Approvals

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3. Problem Statement

There is a growing and persistent need for monitoring and inspection of critical infrastructure around the country and the world. In the United States alone, there are more than 600,000 bridges, one third of which are over fifty years old. These critical infrastructures require surveillance and maintenance in order to ensure that they are structurally intact and not prone to failure. Traditional infrastructure inspection processes have an estimated industry value of USD 1.78 billion in 2019 and are projected to reach USD 5.38 billion by 2027 . In the US, physical infrastructure is overseen by state governments; many long-term partnerships between various states' departments of transportation and infrastructure construction corporations have been formed. Ongoing maintenance of the structures are handled by both the original contractors and dedicated infrastructure monitoring companies. Traditional inspection methods are slow, costly and infrequent. In remote areas, where there is a lack of GPS/GNSS location systems, or rough terrains in which the strenuous accessibility has led to infrequent examinations, there is a need for an autonomous mapping system for remote access and efficient methods of evaluation.

4. Previous Work

LiDAR: Light Detection And Ranging (LiDAR) systems use wavelengths ranging from ultraviolet to near-infrared lasers to determine distances from a sensor. By emitting short pulses of light and comparing phase shifts in the backscattered photons, a 3D model is generated, in the form of a point cloud(source: https://www.nature.com/articles/nature11727). MACULA: LiDAR scanners have been used in previous senior projects such as Mapping Architecture Concept for Universal Landing Automation (MACULA- 2016). This project used LiDAR to detect surface features of potential landing zones for spacecraft to dynamically determine whether the area was safe to land.

SLAM (simultaneous localization and mapping) is a method used to construct a map of the immediate surroundings while localizing the source of the data collection within that map. They are commonly used to give unmanned vehicles the capability of mapping unknown environments in order to plan specific routes and avoid obstacles. A LiDAR SLAM system uses laser sensors as the source of data collection before a SLAM algorithm is implemented. They are used with high-speed vehicles such as self-driving cars and drones. The movement of the system is approximated in real time by matching the point cloud data from the LiDAR. The calculated distance traveled is then used for localization of the system or vehicle. The high accuracy point cloud data from the LiDAR works extremely well with SLAM in the process of map construction when compared to other methods that use cameras and imaging sensors.

5. Specific Objectives

Levels of Success

The project introduced to the group was to design and build a system that could scan and map the undersides of bridges and other structures in order to search for faults, cracks, or other structural points of failure. The team shall design, build, and deploy a Vehicle-based Infrastructure Analysis system using LiDAR, that successfully maps its surroundings while in motion. The most important requirement that was put forth by the customer was that the team needed to utilize a LiDAR system for this project. In addition to this deliverable, the system must also acquire observations from the LiDAR system and be able to transmit collected data wirelessly. A deliverable put forth by the course is that by the end of the project a full design must be defined and implemented into a functioning final project that can be tested for the required functionality. Finally, a deliverable put forth by the group is to attempt to get accurate data from this LiDAR system while at a respectable speed passing under the bridge or structure. With these deliverables the levels of success for each subsystem could be defined. These levels are displayed in Table 1.

Table 1: Levels of Success

Level	Mechanical & Power	Data	Autonomy	Software	Mapping
Level 1	A fixture capable of securing the system shall be fabricated.	Point cloud data shall be collected, but not verified for accuracy (with respect to ground-truth data).	The system shall require driver interaction. The system shall operate in a stationary setting.	Data processing shall be performed after the field campaign.	The system shall generate a map of stationary environments.
Level 2	The fixture shall attach to and detach from a specified vehicle.	The data shall be verified for accuracy (compared with ground-truth data).	——	——	The system shall generate a map of moving environments and periodically update map or localization.
Level 3	The fixture shall attach to and detach from any vehicle. The fixture and all subsystems shall weigh no more than 2.6 kg (5 lb). It shall not require more than 20 W of power. The system shall function in all possible conditions specified by the customer.	The data shall be transmittable up to 185 m (200 yards) from the ground station.	The system shall operate with minimum usage of GPS/GNSS services. The system shall require minimal change in driving behavior.	The software system shall fully function in a moving environment. Data processing shall be performed on-board. Data processing shall be performed in real time.	The system shall continuously map the environment. The system shall have an accuracy of 5 cm and a scanning range of 50m. The system shall utilize a SLAM algorithm for all mapping.

Testing Plan

Each individual critical project element shall be tested:

Electronics/Sensors (Selection of LiDAR System): Different LiDAR systems will be traded (pre-purchase), with one being purchased/obtained by ASTRA, LLC. This system will then be tested on various structures and objects to ensure proper system functionality and accuracy. This will be verified via the obtained Point Cloud data and verifying its accuracy. The test will include processing obtained data in the first scan, compiling and processing it to create the 3-D structure electronically and comparing it to known real measurements of the infrastructure.

Data Transmission: The team's data transmission abilities will be tested in a short-range, wireless environment. This will be done with an RF communications test of sending Point Cloud data to an off base ground station (approx. 200 yards away). Completion of this test will be verified via cross-examination of a known data set and minor processing on the ground station technology. Accurate data comparisons will confirm the viability of the team's wirelessly transmitted data.

Software/Algorithm Development for Data Processing (SLAM Implementation): The team would like to gather SLAM-compatible data. To test whether or not the LiDAR data is SLAM-compatible, the team will run some low-fidelity SLAM algorithms with collected data.

Vehicle Platform: Prior to the first test-mission, the team will secure the LiDAR system to the vehicle, connect all mechanical, electrical, and communicative interfaces, and verify all interfaces are operational via testing. Mechanical/structural interfaces will be tested via visual inspection and a test-drive (ensuring structural stability throughout the drive). The electrical interfaces will be tested in a mission environment (using the vehicles power) and verified via inspection. The communicative interfaces will be tested according to the Data Transmission test plan above.

6. High Level Functional Requirements

With the project clearly defined above, an analysis of the high level functional requirements could be completed. The highest level functional requirement that the team adopted is: **Design, build, and deploy a vehicle-based Infrastructure Analysis system using LiDAR, that maps its surroundings while in motion to a pre-dtermined, scientifically viable level of accuracy.**

This requirement provided a project goal for the team to strive for but does not define how the project will be accomplished. A summary of the high level requirements for each subsystem is also provided for reference. For Hardware / Manufacturing: A functional LiDAR system shall be built that is paired with any other necessary devices in order to conform to the needs of the project, i.e, have a 5cm accuracy and a range of 50m (customer specifications). The LiDAR system shall be compatible with a SLAM algorithm for mapping. For Software: The onboard computer shall function as specified in order to conform to the needs of the project. For Communication: The onboard computer shall upload usable data for future analysis to a homing station that could be up to 183 meter (200 yard) away from the system (customer specified). For Safety Compliances: All aspects of the project will conform to the safety guidelines present by CDOT and the FAA. For Finance: All of the projects finances will sum to less than the $ 5,000 limit unless hardware is donated by outstanding companies or clients.

A second high level requirement was one that the team came up with which falls a bit outside the scope of this project. The team wanted to create a LiDAR system that would work at traffic speeds 60 mph which requires a high quality LiDAR to fucntion correctly. Therefore, this requirement has been modified to: The LiDAR system shall accurately obtain data from its surroundings while moving at a low predetermined (TBD), traffic-law abiding speed. The client has warned us that with the team's budget this may not be possible but it would be a product new to the industry if the team could make it successful at this level of cost. This problem is larger than this project can be but through tireless research and dedicated team members nothing is impossible.

6.1 Concept of Operations (CONOPS)

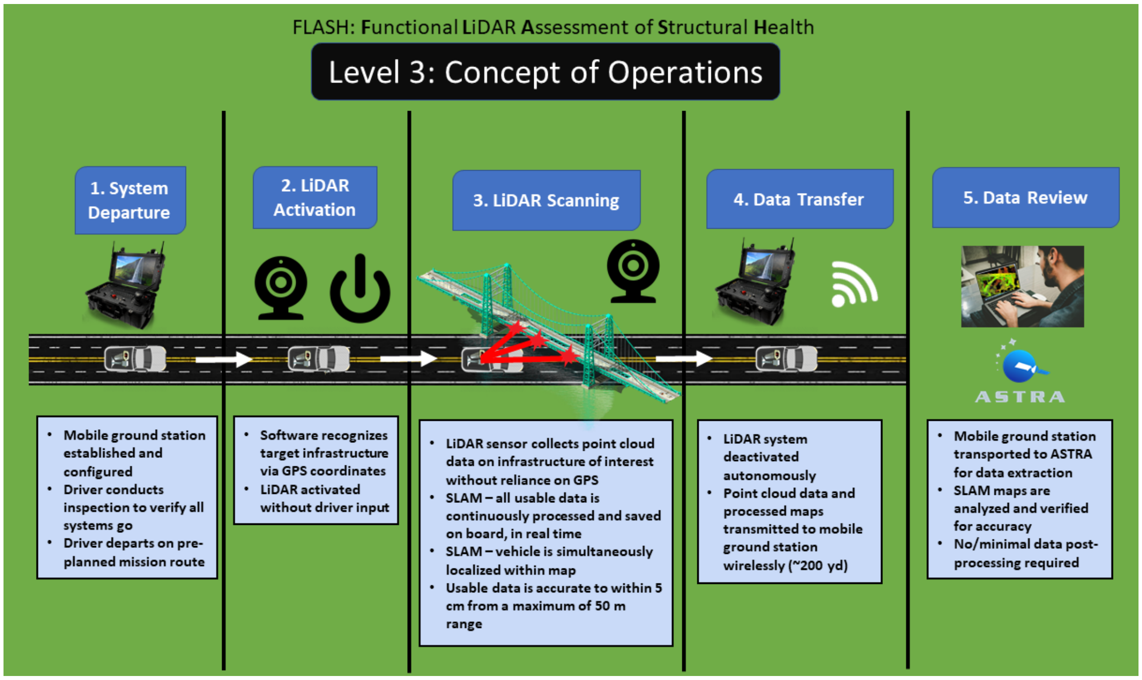

Figure 1: FLASH Level 3 Success Concept of Operations

Figure 1 shows the High-Level CONOPs for the FLASH Vehicle-Based Infrastructure Analysis (VIA) LiDAR System Level 3 mission. The notional infrastructure-specific FLASH mission begins with integration of the LiDAR system to the vehicle. This operation will take place at a mobile ground station, which will be established and configured prior to vehicle departure. Before the vehicle leaves the designated ground station, the mission staff should verify the LiDAR system is secured onto the vehicle. The driver will then depart the mobile ground station on their pre-planned mission route.

Upon reaching the desired infrastructure GPS coordinates (which will be pre-populated into the software system), the LiDAR system will be activated without driver input and data collection will begin. The vehicle driver will adjust their speed in order to match the speed needed for desired LiDAR scanning accuracy. This speed is TBD. The LiDAR sensor will collect point cloud data on the infrastructure of interest without any reliance on GPS. The usable data will be saved and processed on-board the vehicle via a SLAM algorithm. The SLAM algorithm will continuously localize the vehicle and map the vehicles surroundings, real-time and simultaneously. The usable data will be accurate to within 5 cm from a maximum of 50 m range.

Once the data is collected and stored, the LiDAR system will be deactivated autonomously. The vehicle will then arrive at a mobile ground station where close-range (approx. 200 yd) data transmission will occur from the vehicle to the ground station. This mobile ground station will then be transported back to ASTRA for data extraction. This mission notionally requires little to no post-processing of data from the CU team. Level 1 and 2 CONOPs, as well as a SLAM-specific Level 3 CONOPs are included in Appendix A per the costumers request.

7. Critical Project Elements

7.1 Sensor Package

The success of FLASH depends upon the selection of a capable light detection and ranging (LiDAR) system. The use of LiDAR is a customer requirement, but the particular LiDAR system has not been specified. The sensor package must be able to scan infrastructure while in motion and collect data to a 5cm accuracy from a 50m range to allow for 3D mapping and model generation. Acquiring a reliable LiDAR system will likely be the highest project expenditure. Thus, a rigorous trade study will be critical in selecting a reasonably priced system while adhering to functional requirements.

7.2 Software/Algorithm Development

In order to transform the raw LiDAR data into a useful form, a robust software solution must be implemented, likely as part of an embedded system. This will require point cloud processing/registration so that detailed 3D maps/models of infrastructure can be created. In addition, the software shall incorporate a simultaneous localization and mapping (SLAM) algorithm to work in conjunction with the selected LiDAR system. SLAM will enable the system to continuously construct a map of the vehicle's surroundings while estimating the vehicle's location within that map (all in real-time). Software implementation is a critical component of the project because it will likely require the most time and effort. Insightful damage assessment and infrastructure analysis cannot occur without operational software architecture.

7.3 Vehicle Platform

The LiDAR system shall be mounted onto a motor vehicle to allow for autonomous "drive-by" surveying of infrastructure. The mounting fixture must secure all hardware to the vehicle and the structure must incorporate housing to protect hardware from adverse conditions (rain, wind, snow, etc.). Additionally, since FLASH will often operate around other vehicles, the fixture must ensure that the system does not pose a safety concern. A poorly designed vehicle mount may obstruct system performance; hence, this aspect of the project is critical and it presents a challenge in material selection and structural design.

7.4 Data Transmission

The system shall be capable of transmitting point cloud data and supplementary information (date/time, position, unit number) to an established ground station. This wireless transmission shall be possible up to a 183 meter (200 yard) range from the ground station to ensure effective and timely data processing (exact rate to be determined). This aspect of the project poses a challenge because the size of the point cloud data may be substantial and the LiDAR/SLAM system may not be compatible with transmission hardware straight "out-of-the-box".

8. Team Skills and Interests

Table 2: Team Skills and Interests

Critical Project Elements	**Team member(s) and associated skills/interests**
Electronics/Sensors (CPE 7.1)	**Kunal Sinha:** Experience with PCB design and power system design **Fiona McGann:** Experience sensor integration and testing, interest in circuit design **Andrew Fu:** Experience with automation components/systems and circuit design.
Software/Algorithms (CPE 7.2)	**Shray Chauhan:** Experience with MATLAB, interest in point cloud data processing and visualization **Fiona McGann:** Experience with MATLAB, Python, and Arduino, interested in control design **Julian Lambert:** Experience with PLs, OOP, GUIs, and algorithms (additional declared major in Computer Science) **Erik Stolz:** Experience with MATLAB, Python, C++, and Java, interested in control design and data processing
Mechanical/Structural (CPE 7.3)	**Shray Chauhan:** Experience with CAD (SolidWorks, Creo) **Courtney Kelsey:** Experience with CAD (Solidworks, Inventor) **Ishaan Kochhar:** Experience CAD (solidWorks, CATIA V5)
Compliance (all CPEs)	**Jake Fuhrman:** Experience in Systems Engineering **Courtney Kelsey:** Experience with Systems Engineering **Kunal Sinha:** Interest in Project Management **Fiona McGann:** Experience in Project Management
Communications (CPE 7.4)	**Jake Fuhrman:** Interest in Wireless Transmission **Kunal Sinha:** Experience in RF communication **Andrew Fu:** Interest in transmission and processing **Erik Stolz:** Interest in wireless communication
Finance (all CPEs)	**Jake Fuhrman:** Experience with managing budgets (BOM, MEL) **Ishaan Kochhar:** Interest in finance
Testing/Prototyping (all CPEs)	**Shray Chauhan:** Experience with 3D printing (SLA, FDM) **Ishaan Kochhar:** Experience with 3D printing and machine shops, and has designed testing procedures **Fiona McGann:** Experience with lathes, mills, and saws, wire cutters, soldering, and molexing **Ricky Carlson:** Experience with saws, drills, soldering, and 3D printing
Safety (all CPEs)	**Jake Fuhrman:** Experience with Risk Matrix and Regulatory **Ishaan Kochhar:** Experience with Factor of Safety Calculations, interest in Safety

9. Resources

Table 3: Resources

Critical Project Elements	Resource/Source
Vehicle (CPE 7.3)	Team members own cars that can be used
LiDAR (CPE 7.1)	Could potentially cost more than available budget. If cost can be justified, ASTRA has offered help.
Electronics/Hardware for the Mount (CPE 7.1 and 7.3)	Will be bought commercially off the shelf (COS) and modified in one of the project spaces in the Aerospace Building.
Electronics for Data Transmission (CPE 7.4)	Will be bought COS and necessary alterations can be made in the Aerospace Electronics Shop.

References

[1] Comeron, A., Constantino Muñoz-Porcar, Francesc Rocadenbosch and Michaël Sicard (2017). Current Research in Lidar Technology Used for the Remote Sensing of Atmospheric Aerosols. [online] ResearchGate. Available at: https://www.researchgate.net/publication/ 317714590_Current_Research_in_Lidar_Technology_Used_for_the_Remote_Sensing_of_Atmospheric_Aerosols [Accessed 14 Sep. 2020].
[2] American Geosciences Institute. (2017). What is Lidar and what is it used for? [online] Available at: https://www.americangeosciences.org/critical-issues/faq/ what-lidar-and-what-it-used [Accessed 14 Sep. 2020].
[3] Bridges (2017). Bridges. [online] ASCE's 2017 Infrastructure Report Card. Available at: https://www.infrastructurereportcard.org/cat-item/bridges/: :
text=The%20U.S.%20has%20614%2C387%20bridges,structurally
%20deficient%20bridges%20each%20day. [Accessed 14 Sep. 2020].
[4] Mathworks.com. (2020). What Is SLAM (Simultaneous Localization and Mapping) – MATLAB Simulink. [online] Available at: https://www.mathworks.com/discovery/slam.html [Accessed 14 Sep. 2020].
[5] Sun, J., Timurdogan, E., Yaacobi, A., Hosseini, E.S. and Watts, M.R. (2013). Large-scale nanophotonic phased array. Nature, [online] 493(7431), pp.195–199. Available at:
https://www.nature.com/articles/nature11727 [Accessed 14 Sep. 2020].
[6] Matthew Berger, Andrea Tagliasacchi, Lee Seversky, Pierre Alliez, Gael Guennebaud, et al.. A Survey of Surface Reconstruction from Point Clouds. Computer Graphics Forum, Wiley, 2016, pp.27. ff10.1111/cgf.12802ff. ffhal-01348404v2f

References

11. Appendix A: CONOPs Diagrams

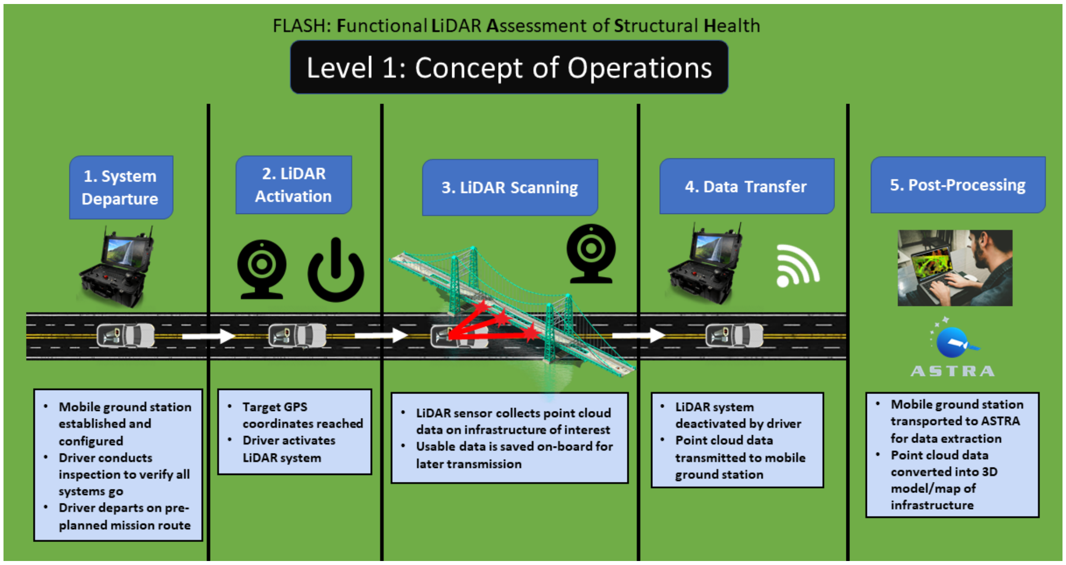

Figure 2: FLASH Level 1 Success Concept of Operations

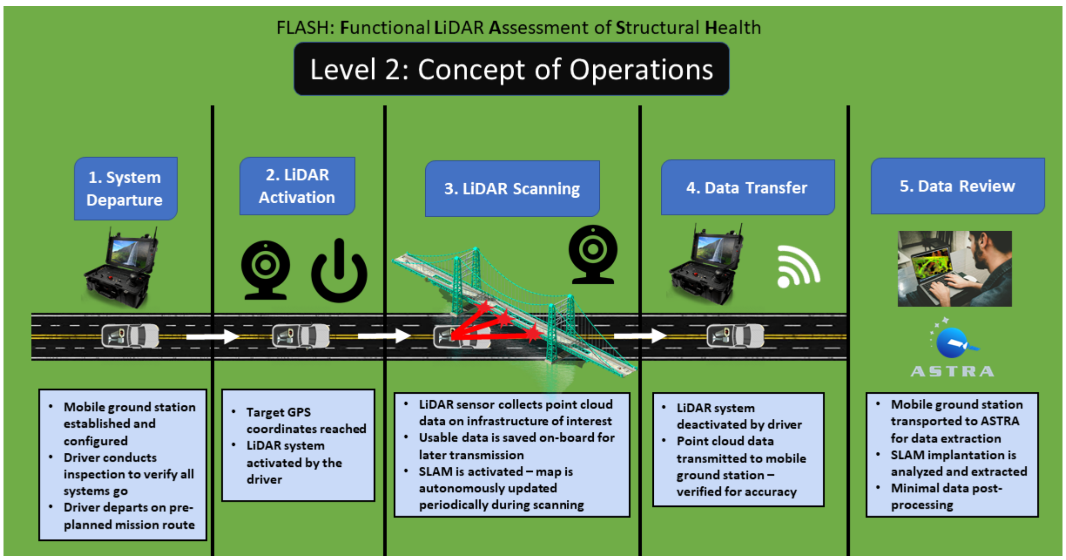

Figure 3: FLASH Level 2 Success Concept of Operations

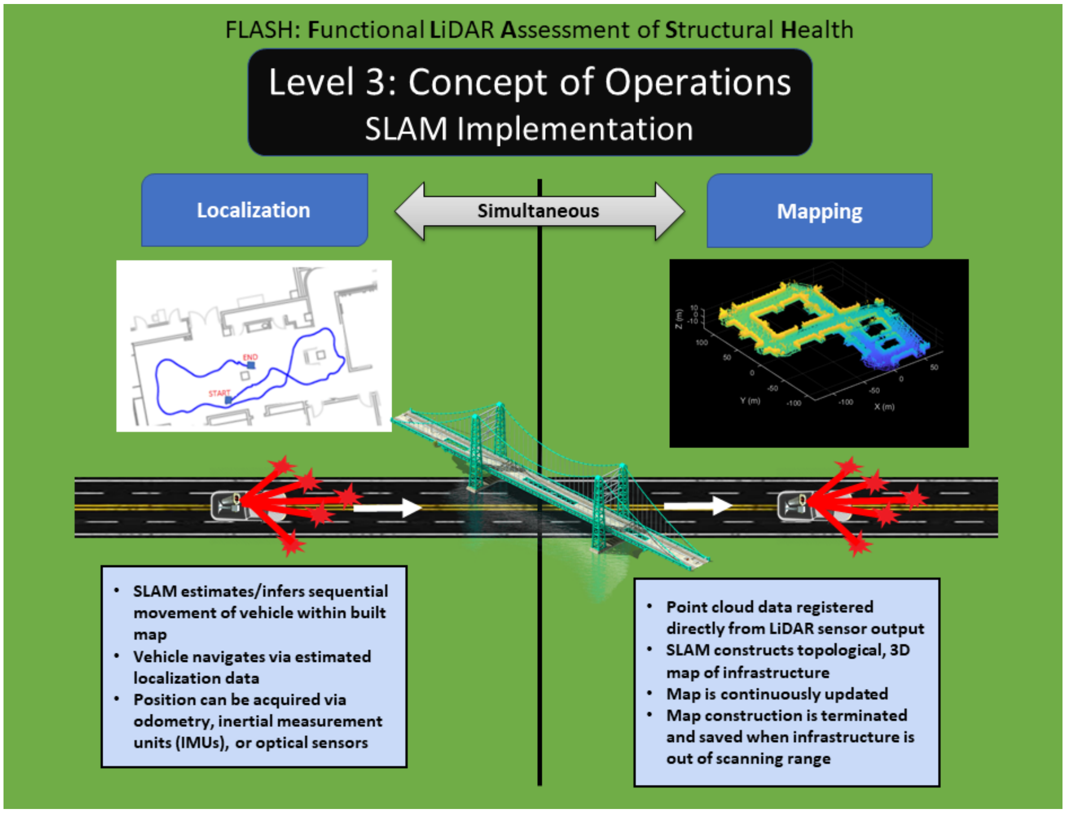

Figure 4: FLASH Level 3 Success - SLAM Implementation Specific - Concept of Operations