University of Colorado
Department of Aerospace Engineering Sciences
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Project Definition Document (PDD)

Mapping Architecture Concept for Universal Landing Automation (MACULA)

Approvals

	Name	Affiliation	Approved	Date
Customer	Jeffrey Thayer	CU AES	Jeffrey P. Thayer Digitally signed by Jeffrey P. Thayer DN: cn=Jeffrey P. Thayer, o=University of Colorado, ou=Aerospace Engineering Sciences Department, email=jeffrey.thayer@colorado.edu, c=US Date: 2016.09.21 16:27:22 -06'00'	
Course Coordinator	James Nabity	CU AES		

Project Customers

Jeffrey Thayer Department of Aerospace Engineering Sciences University of Colorado at Boulder Boulder, CO 80309 Phone: (303) 492-1764 Email: Jeffrey.Thayer@Colorado.edu	Brian Argrow Department of Aerospace Engineering Sciences University of Colorado at Boulder Boulder, CO 80309 Phone: (303) 492-5312 Email: Brian.Argrow@Colorado.edu

Team Members

Arrasmith, Trevor Trevor.Arrasmith@Colorado.edu (720) 301-0237	**Bender, Brett** Brett.Bender@Colorado.edu (440) 488-3321
Brown, Christopher Christopher.J.Brown@Colorado.edu (970) 485-9381	**Dawson, Nicholas** nickdawson95@gmail.com (303) 667-4761
Emmert, David David.Emmert@Colorado.edu (815) 762-1460	**Garby, Bryce** Bryce.Garby@Colorado.edu (303) 570-8276
Gleason, Russell Russell.Gleason@Colorado.edu (425) 281-0805	**Hurst, Matthew** Matthew.R.Hurst@Colorado.edu (303) 506-0501
Levin, Jared Jared.Levin@Colorado.edu (720) 381-9993	**Rothstein-Dowden, Ansel** Ansel.Rothsteindowden@Colorado.edu (774) 392-4555

1 Problem or Need

GUIDED landing of modern spacecraft is often limited in accuracy and application. The inability for a spacecraft to dynamically scan unknown terrain limits potential landing sites to preselected zones with minimal potential hazards. Additionally, the uncertainty in the trajectory of the craft during landing requires that these preselected zones be orders of magnitude larger than the craft itself in order to achieve the desired levels of safety. The result is that the landing zone is often far from areas of scientific interest such as craters or places of high geological activity.

Not only are landing craft limited to these safe zones, but this method requires detailed prior knowledge of the target body's terrain. In cases such as Mars, this is a viable option given the detailed surface mapping that has been obtained from imaging spacecraft in orbit around the planet. Using this approach for other celestial bodies is less viable because it would require multiple missions or additional orbital maneuvers to be able to create a sufficiently detailed map before being able to land on the body.

Having the ability to dynamically detect and avoid obstacles on landing would open up many possibilities for scientific research by allowing these craft to land in areas that would otherwise be too hazardous. This would increase the scientific productivity of rovers by cutting out long travel periods that are expensive to operate and can be physically damaging. Stationary landers could be placed more strategically as well, possibly even removing the need for mobile vehicles on some missions.

The purpose of the MACULA* project is to design, manufacture, and test a light detection and ranging (LiDAR) scanning system that a landing craft can use to dynamically select a safe area on an unknown body. On-board software will detect hazards, making this system both safer and more generally applicable than current systems.

2 Previous Work

Although scanning LiDAR systems have yet to be utilized for entry, descent, and landing (EDL) applications, both scanning LiDAR systems and EDL mapping systems have been previously researched separately.

LiDAR systems are currently used for a wide variety of mapping applications, many of which are similar to the potential applications of this project. In particular, aerial scanning LiDAR systems (see Reigl[1] and NOAA[2]) are commonly used for topographic mapping and bathymetry on Earth. While these systems are not used for hazard avoidance, their mapping systems closely parallel the concepts discussed here. Another similar application of scanning LiDAR is in self-driving cars, such as those made by Google[3]. These cars actively generate maps of their surroundings with LiDAR and use the results to follow the road and to avoid obstacles in the car's path.

Previous EDL systems utilized by National Aeronautics and Space Administration (NASA) missions have relied heavily on Ka-band Doppler radar for range determination and satellite mapping when determining a landing site. The ranging is performed by six Doppler radars in the Ka band that utilize the reflectivity of the ground to scan over a large footprint. For mapping applications, photos taken by satellites at various angles are analyzed to generate a detailed map with height and obstacle information. Using this map, the landing zone is preselected such that the spacecraft landing error ellipse is located in a zone with a low hazard concentration. Given the large landing error ellipse, which can be on the order of 10 km^2, the choice of landing site is often significantly constrained[4].

This project aims to combine these two fields into a LiDAR-based hazard avoidance system for EDL. The advancement that this system provides over existing systems is the in-situ landing determination, enabled by high-precision ranging and mapping. While LiDAR has yet to be used for EDL, the NASA Jet Propulsion Laboratory has done research[5] on scanning LiDAR for EDL and is currently in the process of designing this for use on the Mars 2020 mission. A major difference between their proposed system and the MACULA system is the use of flash LiDAR. Flash LiDAR systems are capable of generating maps in a single pulse by splitting the laser beam, but can cost upwards of $100,000. A mechanically actuated scanning system is significantly slower, but at the same time far less expensive and ultimately capable of generating a similar output. It also provides the added advantage of dynamic resolution.

3 Specific Objectives

The success levels shown below in Table 1 categorize the high-level objectives that must be completed to build, validate, and verify a LiDAR-based dynamic hazard detection and avoidance system. Level 1 success will be met if

*The macula is the part of the eye with the greatest visual acuity.

the system hardware is built, integrated, and tested for functionality. This will include the basic software development required for all subsystems to operate and communicate automatically after high-level user commands have been given. Completion of Level 1 success will result in a physical system that could be used to implement and test hazard detection and avoidance algorithms. Levels 2 through 4 are concerned with development of a hazard detection and landing location selection algorithm, and the mock-up scene required to test it. Level 4 success is the design goal of the team.

Table 1: Success Levels

Level	Hardware: LiDAR Scanning System	Software: Algorithm Development	Test Bed
1	LiDAR sensor and scanning system shall be controlled to obtain measurements of a TBD area with a TBD spatial resolution at a 15m range	Subsystems shall collaborate to record and output meaningful measurements	Stationary platform shall be built to house and operate the LiDAR scanning system
2	Scanning process shall be conducted in less than 60 seconds	Range and attitude measurements shall be translated into a 3D topographic map with propagated uncertainties	Test article with dimensions known to TBD accuracy shall be scanned with LiDAR in order to verify mapping accuracy
3	-	Topographic map shall be analyzed to build a hazard map based on TBD hazard definitions	Test mock-up shall be built with dimensions known to TBD accuracy in order to verify hazard detection and avoidance
4	-	Hazard map shall be analyzed to determine an acceptable landing location based on TBD parameters	-

4 Functional Requirements

4.1 Functional Block Diagram (FBD)

Figure 1 below outlines the flow of functionality in the MACULA system. The system is composed of three principle elements: the user PC controlling the system, the system itself (including the software and electrical components as well as the mechanical scanning subsystem), and finally the test setup. Key elements of the algorithmic flow of information are shown as individual blocks.

4.2 Concept of Operations (CONOPS)

Figure 2 below outlines the high-level mission components within the scope of the MACULA project. The scanning LiDAR system is housed on a landing craft and used to scan the terrain below in the moments before landing on the surface of the target body. Though a specific craft and celestial body are shown here for visual purposes, the LiDAR system is designed to be generally applicable to other landing scenarios.

The LiDAR scanning system activates when the craft is propulsively hovering. At that time, the system performs a scan of the ground below, and then creates a three-dimensional point cloud representation of the terrain. From this point cloud, the on-board software identifies landing hazards on the ground, and then finally identifies the optimal landing zone for the craft to land safely. Testing of this system will involve a stationary platform for the scanning system and a mock-up scene with terrain and obstacles scaled to represent various landing environments.

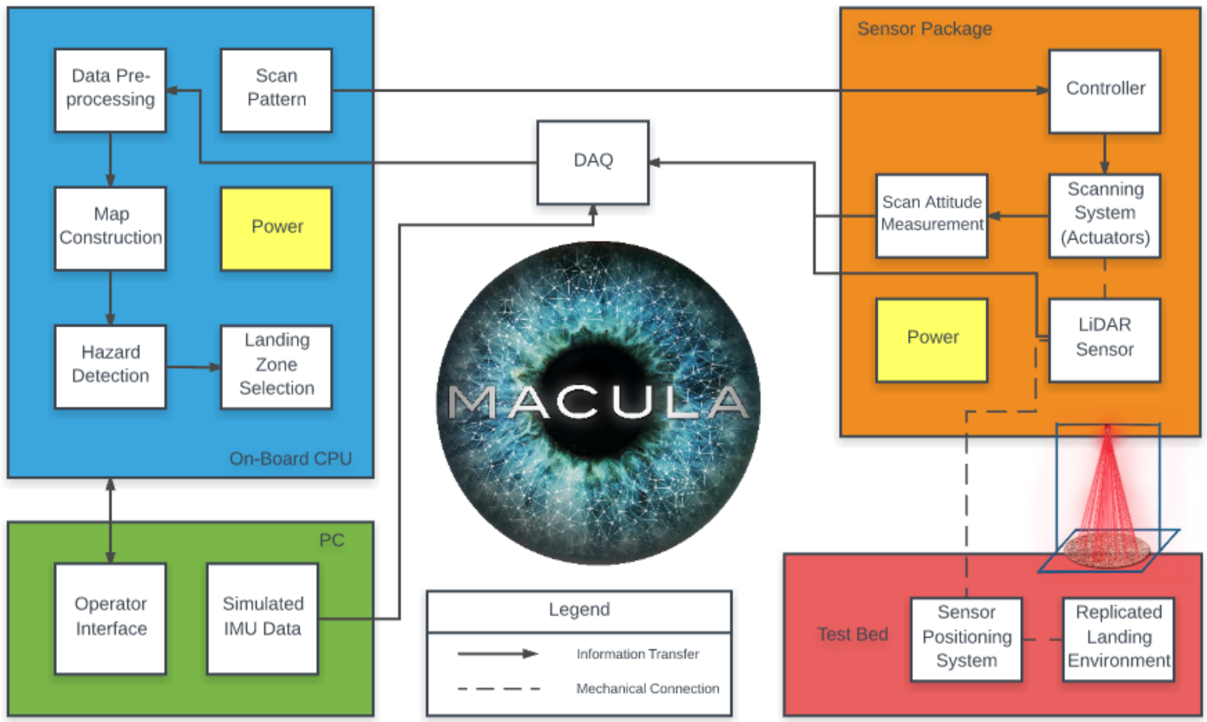

Figure 1: Functional Block Diagram of MACULA System

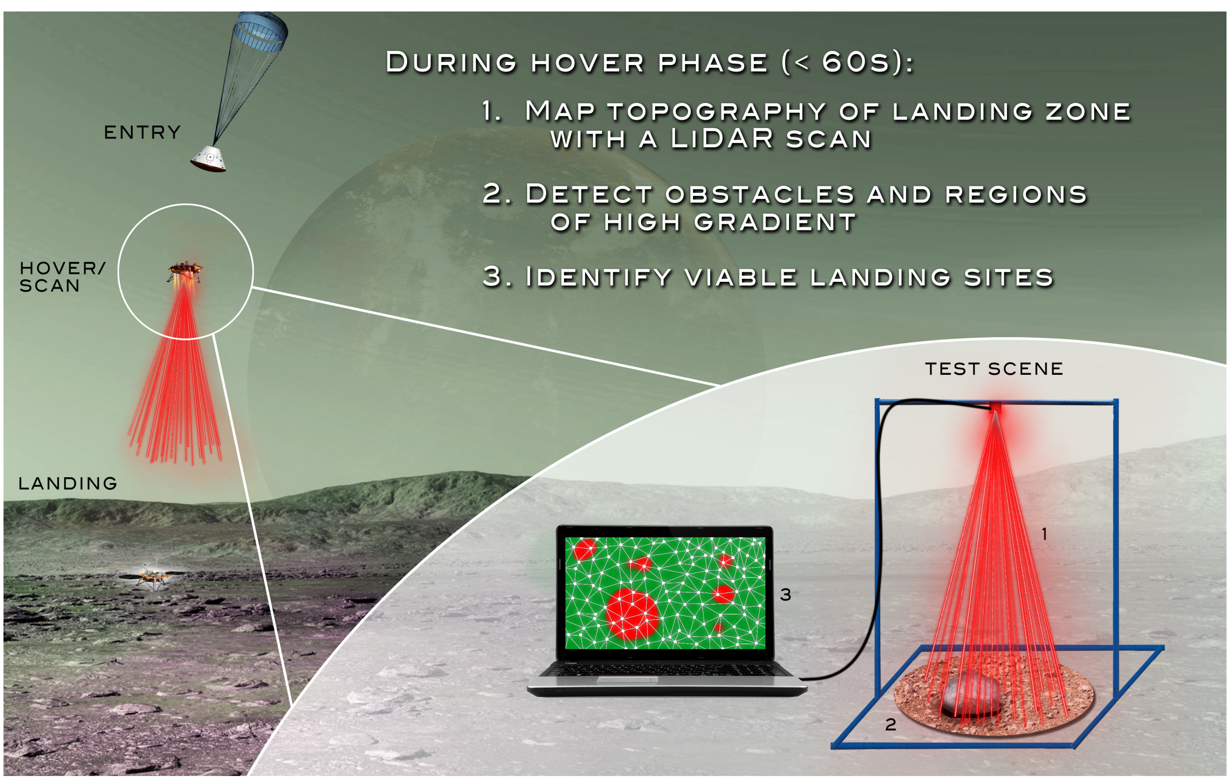

Figure 2: Concept of Operations of MACULA System

5 Critical Project Elements

5.1 Selection of LiDAR Sensor

System performance will greatly depend upon the implemented LiDAR system. The accuracy and precision of the range measurements will propagate into topographic map uncertainty and hazard analysis confidence. In addition, the LiDAR sensor is likely to consume a large portion of the allotted budget. Selection of the LiDAR sensor will be one of the first significant design choices and will affect all future design. Due to the cascading effects and the potential cost of the sensor, the selection of a LiDAR sensor is critical to project success.

5.2 Pointing System Accuracy

For all levels of success, the LiDAR beam direction must be actuated. This requires a gimballed mounting system for the LiDAR as a whole, a rotatable mirror that reflects the beam while the LiDAR remains stationary, or a combination of the two. The pointing knowledge of the scanning system must be known to at least within TBD degrees. This critical design requirement poses significant challenges in gimbal design, actuator selection, and mechanical integration. These components of the scanning system must be selected, purchased, or manufactured, and integrated such that the system can scan a provided area in less than 60 seconds seconds while maintaining a pointing knowledge of TBD. Should these requirements not be met, the scale of the errors in the topographic map will make hazard detection unreliable or impossible.

5.3 Completing a Scan and Analysis in < 60 seconds

Completing a full scan of the required area and post-processing all the necessary data will be challenging given the time constraint of 60 seconds. The system must maintain pointing knowledge during the full scan. This difficulty is prevalent with inexpensive parts, meaning that completing the scan properly will either strain the budget or pose an engineering challenge.

5.4 Software/Hardware Interfaces

The on-board central processing unit (CPU) must be able to receive sensor data, command the actuators, and communicate bi-directionally with a user Personal Computer (PC) for receiving commands and transmitting data. The CPU must be capable of performing the point cloud analysis and sending results to the user PC. This poses a significant challenge in the setup and interfacing of hardware and software. The peripheral devices and the CPU must share communication protocols. The selection of the LiDAR and sensors/motors will drive the selection of the CPU. Certain communication protocols that are common on LiDAR systems, such as TCP/IP Ethernet, may be much more involved in the implementation on embedded devices. These protocols may drive the need for the CPU to support certain third-party libraries, adding complexity to the software. Debugging hardware and software simultaneously will be necessary when working with embedded systems. This debugging has the potential to be very time-consuming and difficult to determine the source of problems. Many of the hardware and software components introduce single-point of failure modes in the system, making the functionality of all components critical.

5.5 Error and Hazard Detection Mathematics

In order to produce an accurate topographic map, as well as an effective hazard detection system, a software algorithm must be constructed with special consideration given to the mathematical implications of the sampling method. This algorithm will determine necessary scanning resolution and pattern such that the landing zone is properly characterized by the three-dimensional point cloud produced by the LiDAR measurements. Mathematics must be developed to define precisely what is meant by “hazard” as well as how to identify them from the point cloud generated by the sensor package. This mathematical application is relatively novel, so the development of these algorithms poses a significant challenge.

6 Team Skills and Interests

Table 2: MACULA Team Skills and Interests

Name	Skills/Interests	CPEs
T. Arrasmith	Experience with software, in particular project management, unit testing, and data parsing. Interest in software development and management and CAD modeling.	5.4, 5.5
B. Bender	Experience with manufacturing, mechanical engineering, and gimballed LiDAR systems. Interest in mechanical and manufacturing.	5.1, 5.2, 5.3
C. Brown	Experience with manufacturing and testing. Interest in manufacturing and dynamics/controls.	5.2, 5.3
N. Dawson	Skilled with programming (C, C++, MATLAB), team collaboration, and systems engineering. Interested in software and testing.	5.2, 5.4
D. Emmert	Experienced with system design and software (C and MATLAB). Interests are systems and software.	5.1, 5.4
B. Garby	Experience with the design of electronic systems, instrumentation, and programming in MATLAB, Python, and C. Previous work with LiDAR systems. Interested in embedded systems, electronics, and low-level programming.	5.1, 5.3, 5.4
R. Gleason	Experience with software, hardware test, CAD, and embedded systems. Interest in software, system integration, testing, and safety.	5.4
M. Hurst	Experience with mathematical modeling, mission operations, and systems engineering. Interest in project management, integration, and testing.	5.5
J. Levin	Experience with software, including C and Python, and systems engineering. Interest in software, systems, and testing.	5.4
A. Rothstein-Dowden	Experience with software, high-level conceptual design, systems, math, and testing. Interest in math, test, systems, and CAD.	5.5

7 Resources

Table 3: MACULA Project Resources

Project Elements	Resource	Explanation
LiDAR Selection	Jeffrey Thayer (Customer)	Knowledge/understanding of LiDAR and scanning system implementation
	Jay McMahon	
	Rory Barton-Grimley	
	Stable Laser Systems	
	Engineering Excellence Fund	Increased budget for LiDAR sensor
Pointing System Accuracy	Trudy Schwartz	Electronics design/integration
	Matt Rhode	Manufacturing expertise
System Time Requirement	Bobby Hodgkinson	Electronics expertise
	Josh Stamps	Mechanical/manufacturing expertise
Software/Hardware Interfacing	Trudy Schwartz	Microprocessors/software integration
Mathematics	John Evans	Computational geometry research
Testing	Matt Rhode	Experience with securing test locations
	CU Facilities Management	Test location resource
	RECUV Lab	Potential indoor testing location
	Balch Fieldhouse	Potential indoor testing location
	Engineering Center Roof	Potential outdoor testing location
	Blender Software	Visualization and test map construction

References

[1] “RIEGL Airborne Solutions.” The RIEGL Newsroom. N.p., 05 Aug. 2016. Web. 31 Aug. 2016

[2] “What Is LIDAR?” What Is LIDAR? National Ocean Service, n.d. Web. 31 Aug. 2016.

[3] Whitwam, Ryan. “How Google’s Self-driving Cars Detect and Avoid Obstacles — ExtremeTech.” ExtremeTech. N.p., 8 Sept. 2014. Web. 31 Aug. 2016.

[4] Way, David W., Richard W. Powell, Allen Chen, Adam D. Steltzner, A. Miguel San Martin, P. Daniel Burkhart, and Gavin F. Mendeck. “Mars Science Laboratory: Entry, Descent, and Landing System Performance.” 2007 IEEE Aerospace Conference (2007): n. pag. Web.

[5] Johnson, Andrew E. “Lidar-Based Hazard Avoidance for Safe Landing on Mars.” JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS 25 (2002): 1-9. AIAA. Web. 30 Aug. 2016. <http://arc.aiaa.org/doi/pdf/10.2514/2.4988>.