Kent State University

Special Project

Nathan Beidle

Systems Engineering 47200

James Zakrajsek

19 April 2023

Requirements Analysis: Europa Probe

Functional Requirements:

The probe shall decouple from the launching mechanism.

The probe shall orbit Europa prior to landing on the surface.

The probe shall scan the surface of Europa while in orbit.

The probe shall send and receive mission critical data while in orbit above Europa.

The probe shall remotely receive a landing course from mission control while in orbit above Europa.

The probe shall land on the surface of Europa after receiving landing coordinates.

The probe shall penetrate ice containing no rocks.

The probe shall collect water samples from the ocean beneath Europa's ice.

The probe shall collect a 2 milliliter water sample at a depth of 0.3 miles.

The probe shall collect a 2 milliliter water sample at a depth of 0.6 miles.

The probe shall collect a 2 milliliter water sample at a depth of 1 mile.

The probe shall collect a 2 milliliter water sample at a depth of 1.3 miles.

The probe shall collect a 2 milliliter water sample at a depth of 1.6 miles.

The probe shall collect a 2 milliliter water sample at a depth of 2 miles.

The probe shall store six 2 milliliter water samples.

The probe shall scan each water sample with an electron microscope.

The probe shall scan each water sample for bacteria.

The probe shall propel itself back to Europa's surface.

The probe shall send test results to mission control.

The probe shall communicate with mission control at all times during the mission.

Performance Requirements:

The probe shall have an operating temperature range of 60°K to 130°K.

The probe shall orbit in a range of 500 km to 1000 km above Europa.

The probe shall remain in orbit around Europa for up to 300 hours.

The probe shall scan the surface of Europa from up to 1000 km above surface level.

The probe shall send terrain data to mission control every 60 minutes.

The probe shall adjust orbit within 60 seconds of receiving new orbit coordinates from mission control.

The probe shall set a landing course within 30 seconds of receiving landing coordinates from mission control.

The vertical speed of the probe shall be less than 9 feet per second at touchdown.

The probe shall operate in an atmosphere consisting of 4% to 8% oxygen.

The probe shall penetrate 15 miles of ice.

The probe shall retrieve all six water samples within 44 hours of touchdown on Europa.

The probe shall store all six water samples at temperatures not exceeding 130°K.

The electron microscope scan shall detect particles of 60 pm or less within saltwater samples.

The bacteria analysis shall detect bacteria at a concentration of 1mg per ml of salt water or less.

The probe shall send the results of all six bacteria analysis tests to mission control within 60 minutes of retrieving the final water sample.

The probe shall send the results of all six electron microscope analysis tests to mission control within 120 minutes of retrieving the final water sample.

Constraint Requirements:

The total weight of the probe shall be less than 150 kg.

The probe shall be no more than 3 ft wide.

The probe shall be no more than 3 ft deep.

The probe shall be no more than 4 ft high.

The probe shall have connectors compliant with Ariane V Payload Adapter System 1663.

The probe shall use electronic buses compliant with IEEE STD 9999.

The probe shall use heritage communication systems.

The probe shall use a 110-watt multi mission thermoelectric radio isotope generator (MMRTG) with a mass of 50 kg.

The probe shall operate in direct sunlight.

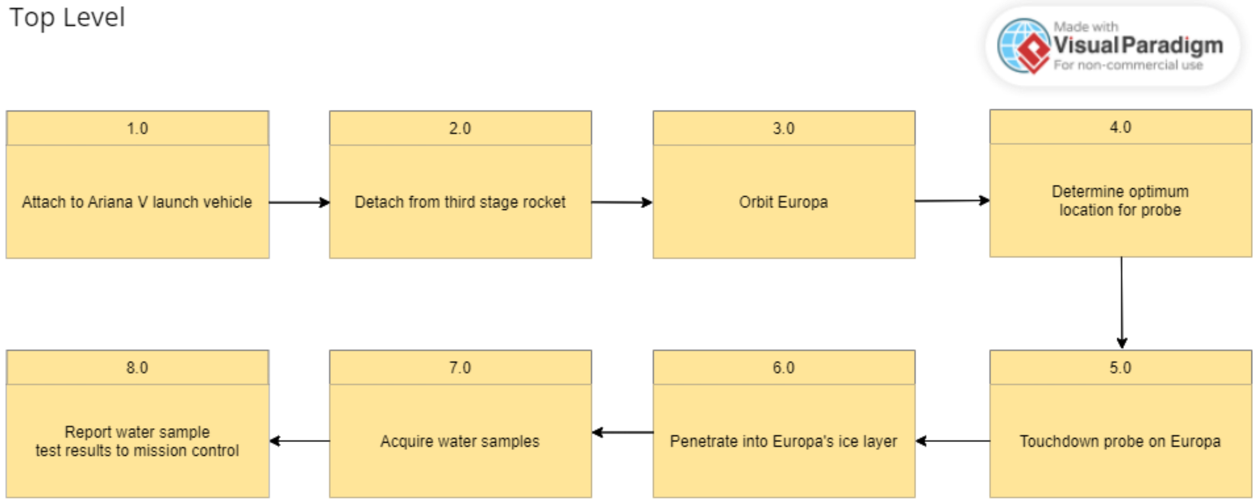
The probe shall operate in an unlit environment.

The probe shall operate in salt water.

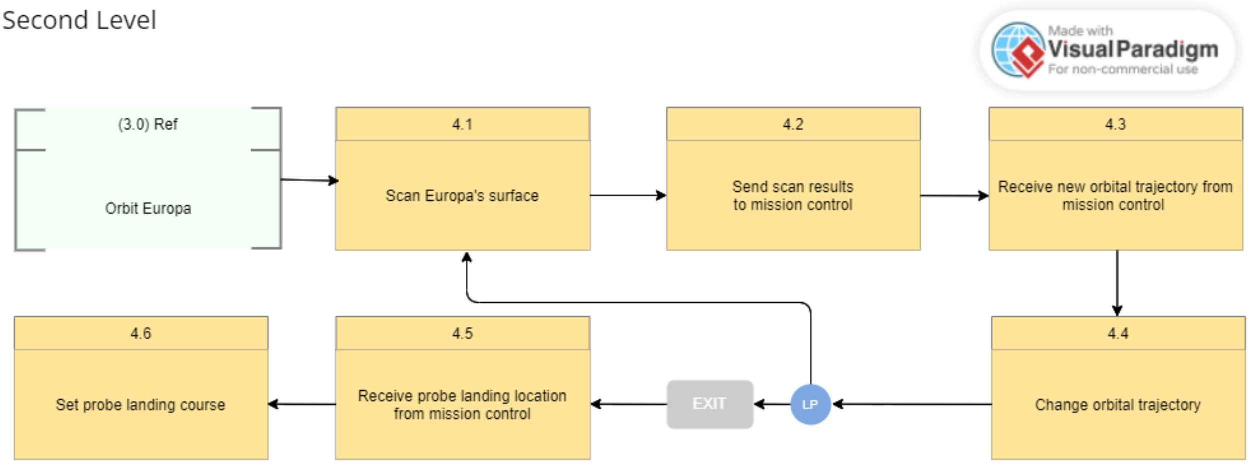
Functional Analysis and Allocation

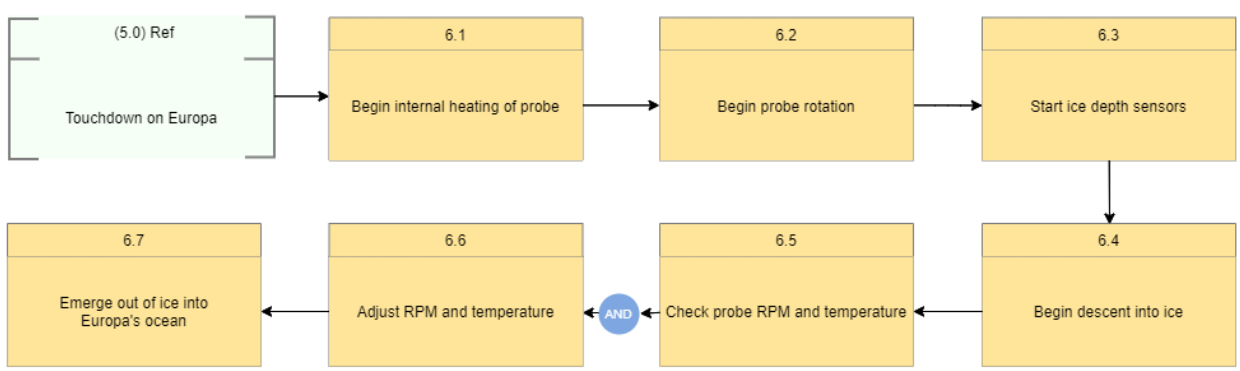
Functional Flow Block Diagram

Top Level

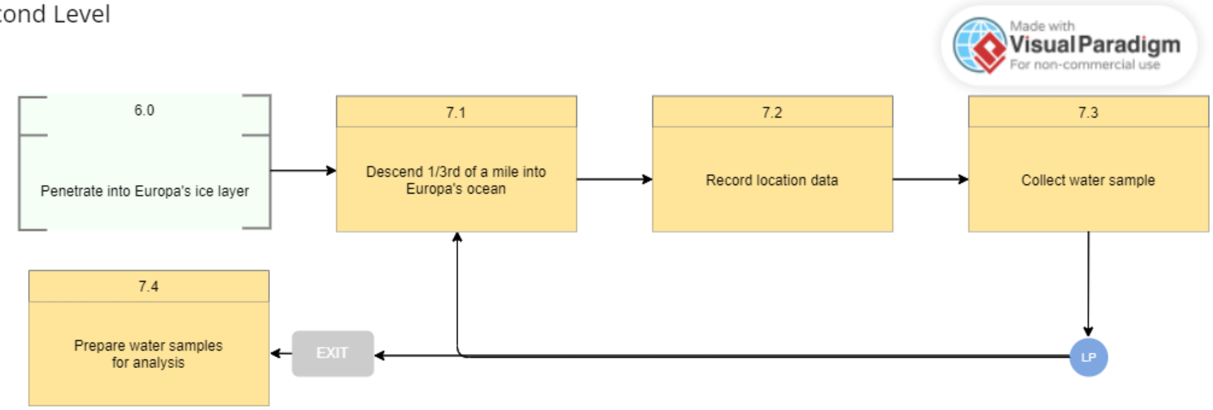


Second Level

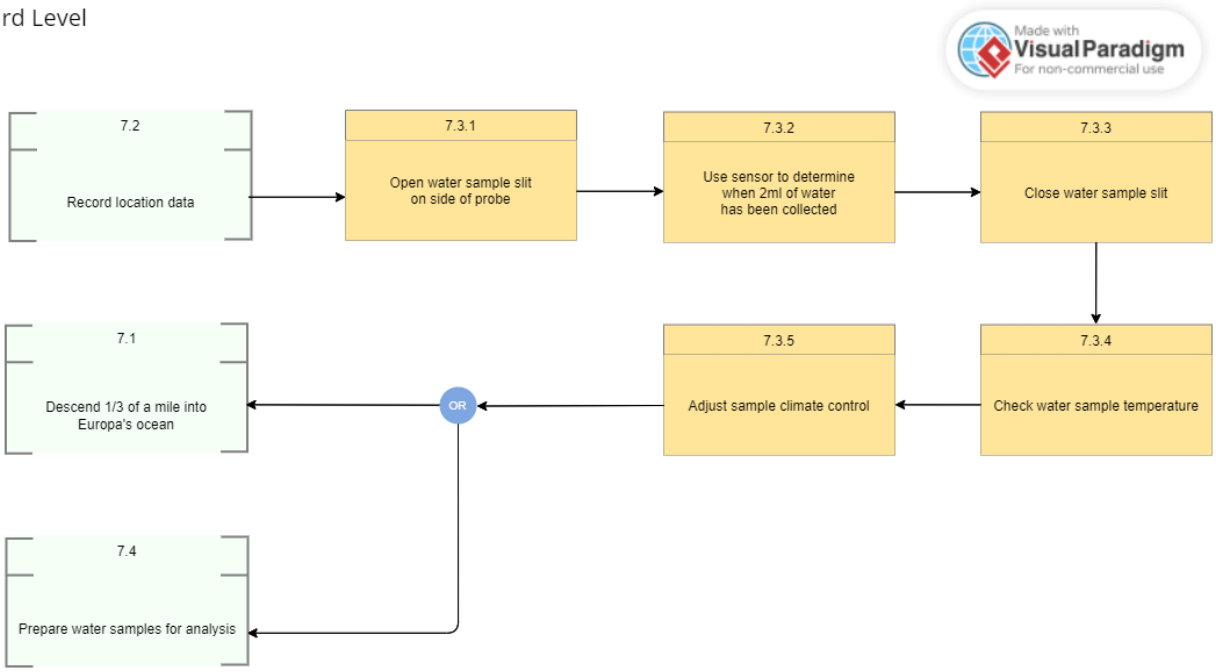




Second Level



Third Level



Functional + Physical Architecture Matrix

[1.0 – 5.0**]**

←Physical→

↑ Functional ↓

[Function Performed]	Coupler	Stabilizers	Terrain Scanners	Heritage Communication System	Probe Onboard Computer
Detach from Ariane V	X				
Orbit Europa		X			X
[Determine optimal landing location for probe]					
Scan Europa's surface			X		X
Send scan results to mission control				X	X
Receive new orbital trajectory				X	X
Change orbit trajectory		X			X
Receive landing location from mission control				X	X
Set probe landing course					X
Touchdown probe on Europa		X			X

Functional + Physical Architecture Matrix

[6.0**]**

←Physical→

↑ Functional ↓

[Function Performed]	Onboard Heating	Drill Bit	Depth Scanners	Probe Status Sensors	Probe Onboard Computer
[Penetrate into ice layer]					
Begin internal heating of probe	X			X	X
Begin probe rotation		X		X	X
Start ice depth sensors			X		X
Begin descent into ice	X	X	X	X	X
Check probe RPM and temperature				X	X
Adjust probe RPM and temperature	X	X		X	X
Emerge out of ice into Europa's ocean	X	X	X	X	X

Functional + Physical Architecture Matrix

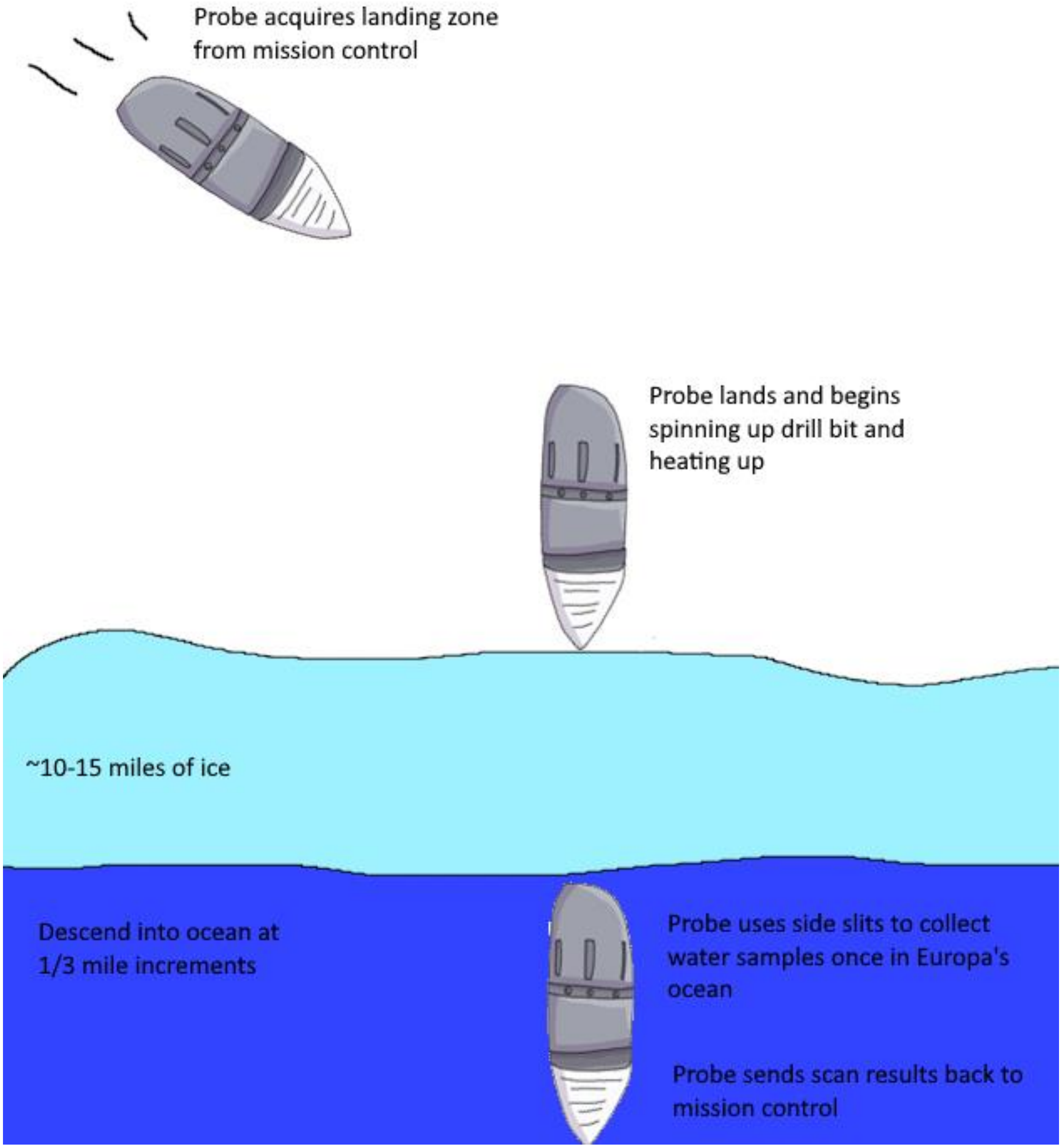
[7.0 – 8.0]

←Physical→

↑Functional↓

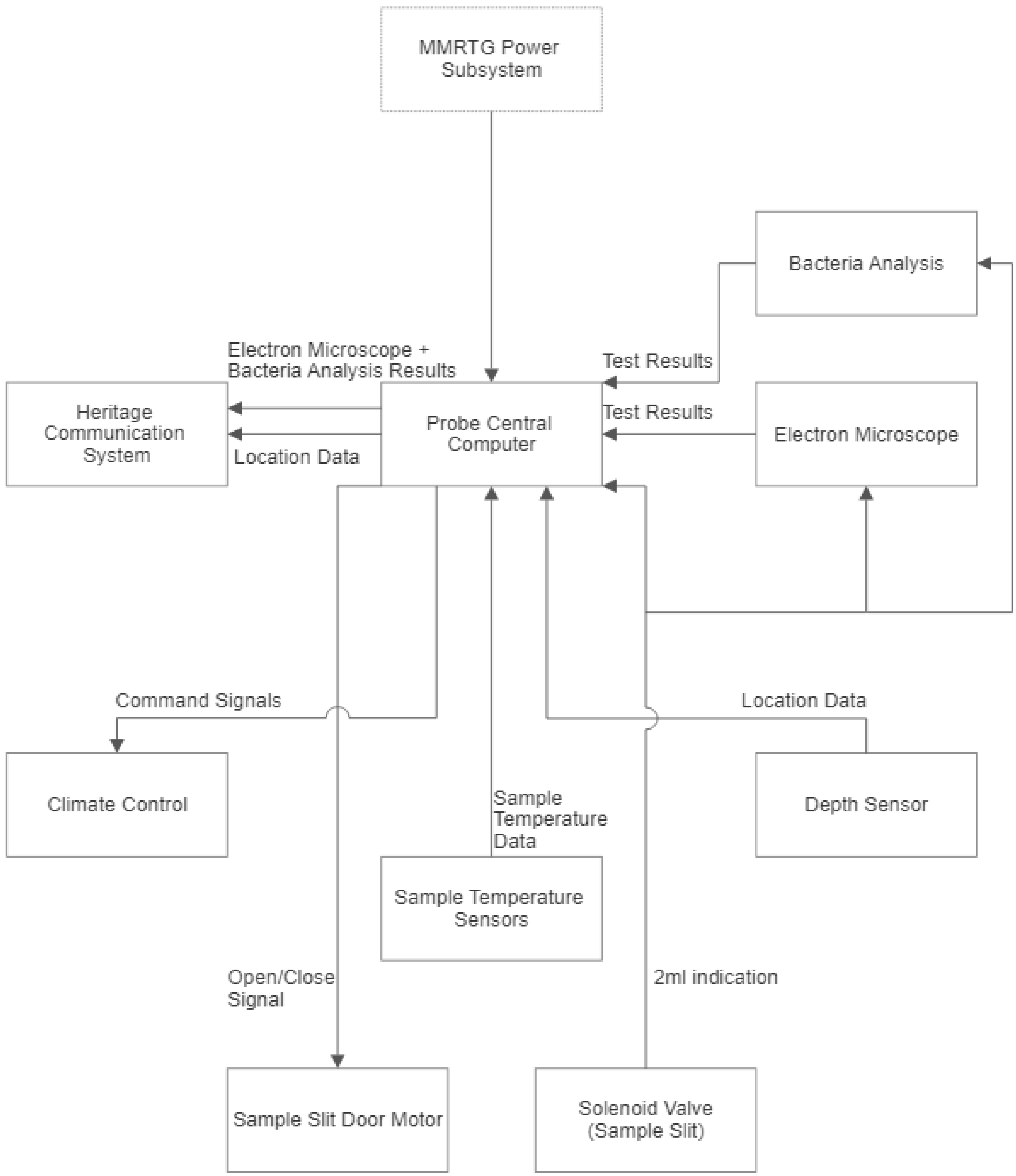
[Function Performed]	Water sample slit	Solenoid Valve	Depth Sensors	Heritage Communication System	Probe Onboard Computer	Electron Microscope	Bacteria Scanner	Sample Temp. Sensor
[Acquire water samples]								
Descend 0.3 miles into Europa’s ocean			X		X			
Record location data			X		X			
Open water sample slit	X				X			
Use sensor to determine when 2ml of water has been collected		X			X			
Close water sample slit	X	X			X			
Check sample temperature					X			X
Adjust sample climate control					X			
Report results to mission control				X	X	X	X	

Concept Description Sheet



Schematic Block Diagram

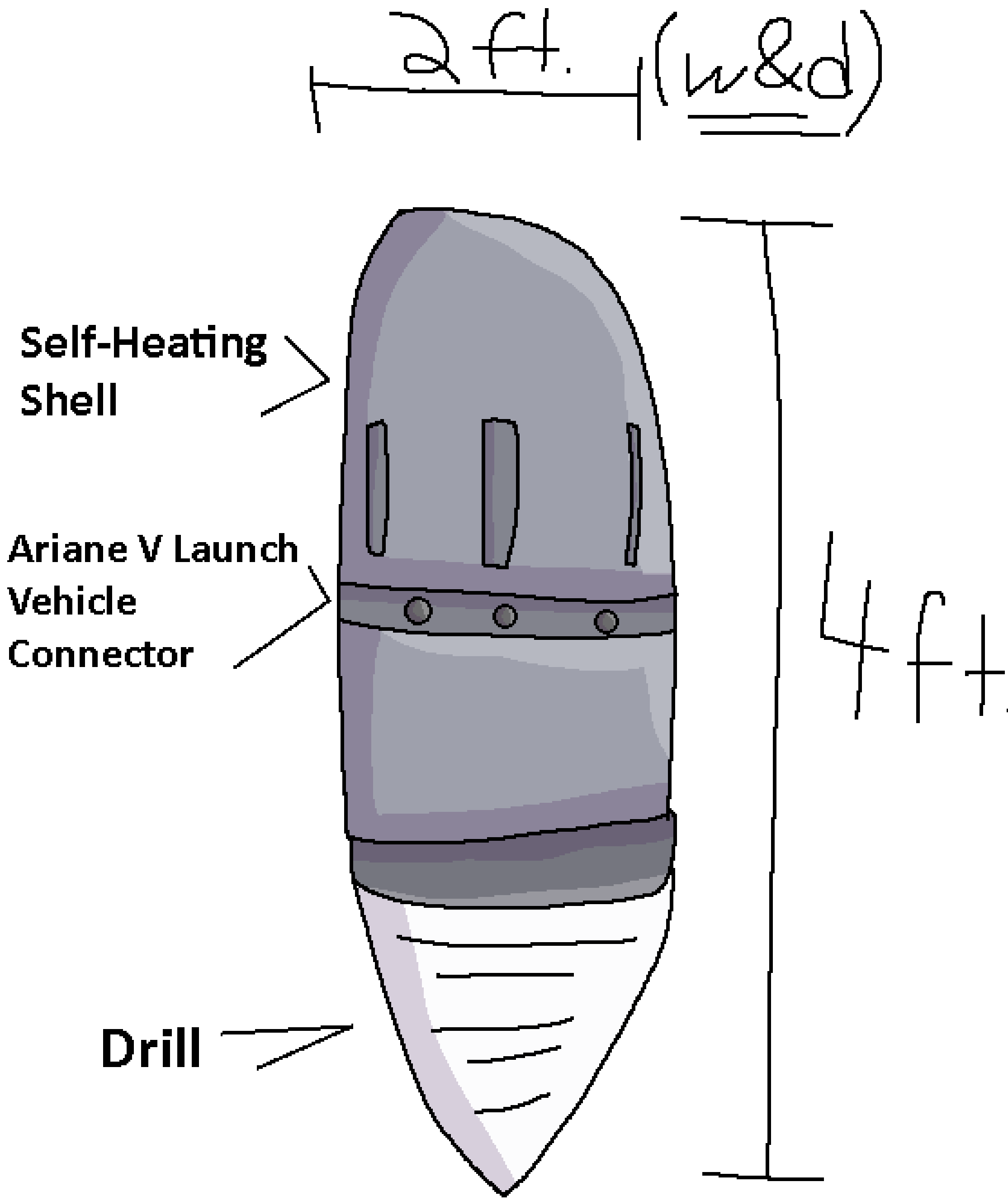
Sample Retrieval Subsystem



Requirements Allocation Sheet

Function Name and Number	Functional, Performance, and Design Requirements	Equipment ID
1.0 Attach to Ariane V	The probe must be able to attach to the Ariane V Launch Vehicle using the Ariane V Payload Adapter System 1663.	Connector Subsystem
1.1 Electronic Bus Compliance	The probe shall use electronic buses compliant with IEEE STD 9999.	Electronics Subsystem
1.2 Weight Requirement	The total weight of the probe shall be less than 150 kg.	Probe
1.2.1 Allocated Drill Weight	The total weight of the drill subsystem shall not exceed 30 kg.	Drill Subsystem
1.2.2 Allocated Power Supply Weight	The probe shall use a 110-watt multi mission thermoelectric radio isotope generator (MMRTG) with a mass of 50 kg.	Power-Supply Subsystem
1.2.3 Allocated Water Sample Collection Weight	The total weight of the water sample collection system shall not exceed 20 kg.	Water Sample Collection Subsystem
1.2.4 Allocated Electron Microscope Weight	The total weight of the electron microscope shall not exceed 10 kg.	Water Sample Testing Subsystem
1.2.5 Allocated Bacteria Analysis Subsystem Weight	The total weight of the bacteria analysis subsystem shall not exceed 10 kg.	Water Sample Testing Subsystem
1.3 Heritage Communication Systems	The probe shall use heritage communication systems designed for previous missions.	Communication Subsystem
1.4 Probe Dimensions	The probe’s overall dimensions shall not exceed 3ft wide by 3ft deep by 4 feet tall	Outer Shell

Sketch


2ft. (w&d)
Self-Heating Shell
Ariane V Launch Vehicle Connector
4ft.
Drill

Requirements Verification Matrix

[1.0-4.4]

Requirement No.	Shall Statement	Verification Success Criteria	Verification Method	Party Responsible for Testing	Results
1.0	The probe shall attach to the Ariane V Launch Vehicle	Successful repeatable docking with Ariane V	Dry run of docking with Ariane V	Ariane V Contracted Support Staff	Probe was able to dock with Ariane V
2.0	The probe shall detach from Ariane V's third stage rocket	Successful repeatable decoupling from third stage connectors	Test decoupling method on scale replica of third stage rocket	Connector Subsystem Team	Test was unable to be completed at this time. Reason: Scale model rocket not ready.
3.0	The probe shall Orbit Europa and be able to adjust orbital path	99.9% success rate on software simulated Orbit paths	Orbital simulation software tests	Software Engineering Department	99.9% success rate was achieved after 2,000 tests.
4.1	The probe shall scan Europa's surface from up to 1000 km away	Successful terrain scans with a 1920x1080 resolution from 1000 km	Test probe's terrain scanning system on a locally launched satellite	Probe Landing Team	Terrain scanning was able to be performed on earth from 1000 km
4.2	The probe shall send terrain scan results to mission control	Successfully encode and send terrain location with heritage encoding within 2 minutes	Use a local satellite already equipped with heritage communication systems to send terrain data	Software Engineering Department	Heritage communication systems were able to encode and send terrain data within 2 minutes
4.3	The probe shall receive a new orbital trajectory from mission control	Successfully decode a new trajectory from mission control within 2 seconds of receiving a data packet	Use a local satellite already equipped with heritage communication to receive orbital trajectory data	Software Engineering Department	Heritage communication systems were able to decode orbital trajectory data within 2 seconds
4.4	The probe shall change its orbital trajectory	Successfully self-correct to a new orbital trajectory	Use a scale model of the probe to test orbital correction system in simulated low gravity environments	Hardware Engineering Department	The scale model probe was able to self-correct trajectories in simulated low gravity environments.

Requirements Verification Matrix

[4.5-6.5]

Requirement No.	Shall Statement	Verification Success Criteria	Verification Method	Party Responsible for Testing	Results
4.5	The probe shall receive a landing location from mission control	Successfully decode and program a landing location within 30 seconds of receiving a landing data packet	Use a local satellite already equipped with heritage communication to receive and decode a landing location	Software Engineering Department	Probe was able to successfully decode and program a landing location within 30 seconds of receiving the data packet
4.6	The probe shall detach from Ariane V’s third stage rocket	Successful repeatable decoupling from third stage connectors	Test decoupling method on scale replica of third stage rocket	Connector Subsystem Team	Test was unable to be completed at this time. Reason: Scale model rocket not ready.
5.0	The probe shall touchdown on Europa	Successfully land probe within a 1 square meter target zone	Use a scale model probe to test landing procedure and subsystems	Probe Landing Team	Scale model probe crash landed. Test failed.
6.1	The probe shall heat its outer layer to 75°C	Successfully heat the probe to 75°C within 5 minutes with a starting temperature of -40°C	Use the probe’s heating system while in a climate controlled lab environment	Hardware Engineering Department	Probe was able to successfully heat itself to 75°C within 5 minutes with a starting temperature of -40°C
6.2	The probe shall spin itself to penetrate the attached drill-bit through Europa’s ice layer	Successfully spin probe up to 90% speed within 10 minutes	Transport probe to Antarctic and conduct testing while on ice sheet	Remote Research and Development Team	The probe was able to successfully spin up to speed on 9 out of 10 tests.
6.3	The probe shall internally sense its depth within Europa’s ice layer	Successfully capture depth location data within a tolerance of 1 meter	Drop depth subsystem into the Atlantic Ocean and record location data	Remote Research and Development Team	The probe was able to detect its depth without external assistance within a tolerance of 1 meter
6.4	The probe shall penetrate 15 miles of ice within 44 hours	Successfully drill through ice at a speed of at least 0.34 miles per hour	Transport probe to Antarctic ice to conduct testing while on ice sheet	Remote Research and Development Team	The probe was able to drill into the Antarctic ice at a speed of 0.34 miles per hour
6.5	The probe shall self-adjust shell temperature and drill speed	Successfully maintain 90% drill speed and 75°C probe temperature for 50 hours	Run a 50 hour test on the probe while in a block of ice	Hardware Engineering Department	The probe was able to maintain 90% drill speed and 75°C probe temperature for 50 hours

Requirements Verification Matrix

[7.0-8.0]

Requirement No.	Shall Statement	Verification Success Criteria	Verification Method	Party Responsible for Testing	Results
7.0	The probe shall perform controlled 0.3 mile descents	Successfully drop probe in an open body of water at 0.3 mile increments	Transport probe to Atlantic Ocean and perform controlled descents	Remote Research and Development	Probe was able to successfully able to perform controlled 0.3 mile descents
7.3.1	The probe shall be able to open water sample slits located on its sides	Successfully open water sample slits while fully emersed under water	Open and close water sample slits while underwater at lab pool	Hardware Engineering Department	The probe was able to open and close water sample retrieval slits while under water
7.3.2	The probe shall close water sample slits when exactly 2ml of water has been collected	Successfully close water sample slits at exactly 2ml	Collect exactly 2ml of water while underwater at lab pool	Hardware Engineering Department	The probe collected exact 2ml samples in each test
7.3.4	The probe shall maintain the water sample at 130°K	Successfully cool a water sample within the probe to 130°K and maintain temperature for one hour	Use the probe’s water sample cooling system on a water sample	Hardware Engineering Department	Probe was able to successfully cool a water sample to 130°K for one hour
7.4.1	The probe shall conduct a bacteria analysis on the six 2ml water samples	Successfully perform a bacteria analysis on 2ml of saltwater with a 1 mg per ml accuracy using the probes bacteria analysis subsystem	Test water samples with varying levels of bacteria concentration using the probe bacteria analysis subsystem	Biological Discovery Team	The probe’s bacteria analysis subsystem was able to detect bacteria down to a concentration of 1mg per ml of saltwater
7.4.2	The probe shall conduct an electron microscope scan on the six 2ml water samples	Successfully perform an electron microscope scan on 2ml of saltwater with a 60pm accuracy using the probe’s electron microscope	Test water samples with varying levels of contaminate concentration using the electron microscope.	Biological Discovery Team	The probe’s electron microscope was able to detect contaminates as small as 60pm
8.0	The probe shall send the results of all onboard tests back to mission control	Successfully send a data packet containing test results and location data to mission control	Use a local satellite equipped with heritage communication to send a packet containing test and location data to mission control	Remote Research and Development Team	The local satellite was able to send test and location data

Alternative Ice Penetration Mechanisms

Instead of using a drill, several other alternative designs have been considered:

Laser Drilling:

The probe's drill bit section would be supplemented by lasers on the side of the probe used to melt Europa's ice layer. These lasers would have a focal point near the end of the drill bit allowing for easier penetration and less wear on the drill bit.

Explosive Drilling:

The probe would drop explosive charges on the landing zone prior to touchdown to reduce the amount of ice the probe must penetrate. The probe would need to have the ability to pinpoint the touchdown destination with an explosive payload from orbit. The probe would also need to repeatedly hit the same location to cause controlled terraforming.

Instead of collecting samples via slits in the probe, several other alternative designs have been considered:

Singular Opening:

The slits on the side of the probe would be replaced by a singular opening on the top. This opening would separate the probe into six different chambers allowing each sample to be acquired independently. The central tube along with any other area where multiple water samples pass through will need to be sanitized to prevent contamination between samples.

Remote Testing:

The probe's internal electron microscope and bacteria scanner would instead be replaced by a remote testing site deployed by the probe on Europa's surface. This solution would require several new mechanisms as well as a reallocation of several mechanisms. The most important new component to this solution would be an umbilical running between the testing site on Europa's surface and the probe itself. However, this solution presents several unique benefits as well such as having a communications base stationed on Europa's surface, having a smaller payload needed to go through the ice, and the umbilical could be used as a method to retract the probe once it has retrieved the samples.

Trade Studies

To ensure the most effective solution functionally and economically, studies were conducted on several of the probe’s modules. The results of these studies are summarized below.

Drilling Mechanism:

	Cost to implement (millions of dollars)	Weight (kg)	Ice penetration per hour (miles per hour)
Drill Bit (no lasers)	1	20	1
Lasers (no drill bit)	2	30	2
Drill Bit + Lasers	3	50	5
Explosives	2.5	75	(Reduces amount of ice on surface by up to 2 miles)

Based on the results above, it would not be feasible to include explosives due to their high cost, high weight, and low impact. Lasers could be implemented to supplement the drill bit but are not necessary as the drill bit alone will penetrate the ice in time.

Sample Acquisition Mechanism:

	Cost to implement (millions of dollars)	Weight (kg)	Time needed to acquire samples (seconds)
Multi-Slit	0.5	4	2
Singular Opening	1.5	7	8
Remote testing	10	35	90

Based on the results above, it would not be feasible to include remote testing due to its high cost, high weight, and long acquisition time. In addition, remote testing requires the development of many mission specific modules, which will add technical overhead. The multi-slit opening is the most efficient method of sample retrieval based on the given studies.

Assumptions

All time increments were assumed. This includes but is not limited to:

- Orbit time – assumed to be up to 300 hours.
- Time to penetrate ice – assumed to be about 44 hours.
- Time to send and receive signals from mission control – assumed to be around 30 minutes.

Many aspects pertaining to the launching of the probe from the Ariane V were assumed. Those aspects mainly consisted of how the probe would couple and decouple from Ariane V's third stage rocket.

The capabilities of the heritage communication system were assumed. It was assumed the communication system worked while on Europa and it was assumed the heritage communication system could send and receive information from mission control in roughly 30 minutes.

The exact percentage of oxygen on Europa's surface was assumed to be in the range of 4% -8%.
The accuracy needed of the electron microscope was assumed to be 60pm.
The bacteria analysis was assumed to be accurate in determining bacteria concentrations as little as 1mg/ml of salt water. The bacteria analysis was assumed to take two hours.

In addition to assumptions made, many mechanisms were left in high level concept designs, due to the scope of the project. These black-boxed mechanisms include but are not limited to:

- The probe's Ariane V Launch Vehicle connector
- The climate control system
- The internal scanners and system diagnostics
- All gyroscopic stabilizers
- All speed stabilizers

References

“Ariane 5.” Arianespace, ArianeGroup, 17 Feb. 2021, https://www.arianespace.com/vehicle/ariane-5/.

“Hubble Finds Oxygen Atmosphere on Jupiter's Moon Europa – NASA's Europa Clipper.” *NASA*, NASA, 28 Sept. 2020, https://europa.nasa.gov/news/18/hubble-finds-oxygen-atmosphere-on-jupiters-moon-europa/.