University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Project Definition Document

DRAGON

Deployed **R**F **A**ntennas for **G**PS-denied **O**ptimization and Environmental **N**avigation

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Approvals

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1. Problem Statement

The field of autonomous navigation is prevalent in a variety of environments, from Martian deserts to battlefield urban canyons; as such, the availability of GPS is never guaranteed. Presently, autonomous navigation without GPS is limited to small scale, high error, inertial/odometry dead-reckoning measurements, or to highly complicated visual-inertial systems using stereoscopy. In the context of this project, we envision a remote scientist with two goals: to investigate specific waypoints within a GPS-denied area using a rover and to collect short/long term environmental data of the area. The investigation goal is carried out by the rover navigating to each waypoint, which will be accomplished by using deployed beacon pods for RF-localization in lieu of GPS. The short/long term environmental data collection goal is also completed by the deployed beacon pods.

The rover will determine its location relative to an accurate last known position by using inertial measurements. The crux of this project is to supplement and correct the rovers inertial navigation measurements with distantly-deployed RF-localization beacon pods. The RF-localization beacons and software are pre-developed and supplied by the customer; they are not expected to add additional workload to the team. The customer supplied RF-localization beacon transponders will be integrated into the deployable pods in addition to an environmental science data collection sensor suite. This combination is referred to as the pods henceforth. The team-developed software will generate an optimal path to waypoints based on user and terrain data, and the software will determine where to deploy the pods. The optimal path implies a balance between terrain limitations, user-desired waypoints, and beacon pod deployment location. Beacon pod deployment location implies a balance between the need to improve rover navigation capability, and the ability to collect valuable environmental data. The value of environmental data is determined by a scientist-supplied heatmap of high-science-interest areas. The balancing will be determined by a weighting algorithm that will consider both desired goals of the pod by assigning weights to them.

As a secondary objective, the beacon pods will remain in their deployed location long after the rover has passed and continue to collect scientific data, operating in a low power standby configuration. At this point, they can be contacted by any nearby rover and again assist in navigation, or transmit the collected data.

The DRAGON team will provide a fully autonomous method to improve localization in complex GPS-denied environments, with the secondary mission being that these beacons will remain in the environment for future exploration while collecting intermittent scientific data. With respect to the complexity of this project, and the duality of our customer-required mission objectives, DRAGON explicitly summarizes that the project focus is improvement of navigation, and is supplemented by environmental science data collection.

2. Previous Work

The main tool of trailblazers throughout history has been the map; which is limited when navigators reach map's edge. GPS has been used to exceed this fundamental limitation by providing accurate location and terrain information anywhere on the globe. Older navigation techniques required one's location relative to the North Pole and nearby landmarks in order to map out new terrain in near real-time. Modern navigation uses timing or signal decay to measure exact distances between the receiver and the source. This technique is used by GPS, as well as smaller scale RF-localization. Over a decade ago, the University of Minnesota showed the feasibility of using RF transmitters with known locations to determine the location of a receiver to within a sub-meter accuracy[4]. Although there has been a lot of research regarding RF Localization, there does not appear to be any commercial version of the positioning system. Most cases appear to be indoor positioning systems and piggybacking off of other technologies to gain positioning such as cell phones[5].

This project is centered around localization and navigation of a rover– a *Jackal*[3] model COTS rover, purchased from Clearpath Robotics. The Jackal comes with a 270 watt hour battery, up to 20 pounds of payload capacity, 2 64-bit on board computers built with ROS and Linux functionality, and built in GPS and IMU components. This allows the Jackal to support a wide array of operating conditions to allow for on-board localization and mapping to traverse a large featureless area. The Jackal also has an upgraded storage capacity allowing environmental data to be saved. There are also two different payload mounting areas on the top over the rover, sized 135 mm by 135 mm and 300 mm by 180 mm, respectively. The size of the payload mounting areas along with the payload capacity allow for design freedom in terms of a deployment system for the pods as well as housing multiple pods on-board before deployment.

Last year, project RAVEN (sponsored by Dr. Ahmed) used the Jackal rover as an unmanned ground vehicle (UGV). RAVEN demonstrated complex control and integration of custom software on the rover, much of which may be reused by DRAGON. However, RAVEN focused on optical tracking using a UAV, so many of their results will not help DRAGON directly.

The software planned for this project derives its heritage from SLAM implementations developed over the past three decades. SLAM, otherwise known as Simultaneous Localization and Mapping, is a family of algorithms that allow a robot/vehicle to calculate its pose in its environment while simultaneously generating the map of its surroundings to generate its next location. This method was pioneered in the mid-1980s[2] and uses methods like Extended Kalman Filtering and maximum a posteriori estimation to extend robot autonomy in completely unknown terrain. The software for Project DRAGON will be a subset of SLAM, more related to marker based tracking, as the rover itself will start with an initial pose in its environment from the GPS and will then regenerate its path and map through the use of the RF beacons and on-board sensors. This will involve heavy use of Kalman Filtering and Bayesian statistical methods.

DRAGON will go about RF Localization in a new way by implementing pods that are able to be deployed remotely. These pods will be capable of acting as RF beacons as well as environmental sensors. Previously, the beacons were placed in absolute known locations using location systems such as GPS, but this project will introduce the idea of being able to deploy pods whilst navigating to improve accuracy.

3. Specific Objectives

The levels of success (LOS) have been broken into categories for each major element of project DRAGON. Each category has a minimum "Level 1," which are defined as the most basic criteria of success for the project. Level 2 is a more intermediate set of accomplishments which describe the customer's excepted outcome, while Level 3 defines the total completion of customer specified objectives. Level 4 consists of difficult goals defined by the customer to be completed if time and budget permit. Each level of success acts as a funnel towards the next objective in each project element category. Lower levels represent simplifications to the project if a requirement goal becomes unachievable with the given amount of time. Table 1 describes each project element in each row and the level of success o be achieved in the columns. A project element is referenced in the table by its abbreviation, while a previous level is compressed to L#. For example, referring to the first level of success for rover navigation would be abbreviated as RN-L1. In addition, square-bracketed numbers, such as [1], reference additional information at the bottom of the table.

In addition, the DRAGON team has intent to develop a Ground Segment (GS) that is not directly demonstrated in the LOS. The GS will have two development stages. The first will have only remote Emergency Power Off (EPO) and rover state indication. All data will be stored on the rover and analyzed in post. This is implied in the 1st and 2nd LOS, in the way that no test can be performed safely without EPO capability, and post-test data analysis is sufficient for proof of concept and well understood by the team. The second stage of development for the GS, implied in SW-L4, will include online (real-time) telemetering of various rover data such as location and operational monitoring parameters. This data will be received and presented in a GUI such that data can be presented live during a test for monitoring.

Project Elements	Level 1	Level 2	Level 3	Level 4
Rover Navigation (RN)	The rover can locate itself within a deployed pod array to an accuracy of 1m using RF localization, after a short (15m TBR) pilot controlled traversal. [1]	The rover autonomously completes RN-L1 using computer closed loop location error correction. Correction uses relative position data from pods to correct dead reckoning to 1m TBR. [1]	Rover autonomously maneuvers along the SW-L1 path. Rover uses RN-L2 to reach all 5-10 (TBR) waypoints within 1m TBR tolerance.	RN-L3 and reaches waypoints within user specified times and within 30 seconds (TBR) of user specified times.
Pod Deployment (PD)	Pods are hand placed, in analytically [2] predetermined locations.	Pod deployment system on the rover has a range capability of beyond 10m. Pods are deployed within a 1m TBR radius of intended absolute location. User inputs trajectory.	Software provides desired pod location. Deployment system uses rover-based software to calculate trajectories and commands to deploy.	
Scientific Data (SD)		Pods functionally collect TBD environmental data.	SD-L2 and the rover is able to selectively request/receive data from pods. [3] Pods collect environmental data at 5 minute frequency (TBR).	The pods are able to communicate amongst themselves using a mesh network, such that only communicating to one pod enables access to all deployed pods data.
Pod (PO)	Pods will continuously broadcast RF-localization signals using required presupplied beacons. Broadcast will be received and recorded by the rover (via RN-L1).	Pods can transmit environmental science data, in addition to RF-localization data, to rover. Pod internal components can function after deployment stresses.	Pods demonstrate ability to toggle between low-power data recording mode (10mA TBR) and high-powered transmission mode (500mA TBR).	Pods records TBD environmental observations for a 2 hour TBR duration in low-power mode after navigation completion.
Software (SW)	Software can determine a path for the rover to get to (5-10 TBR) waypoints around obstacles and hazards, using terrain map and user specified waypoints.	SW-L1 and software can determine pod placement which will provide online correction assistance to rover along SW-L1 defined path.	SW-L2 and software can determine pod placement which will balance pods dual function of assisting rover, and collecting science data. [4]	Ground segment provides online [5] communication with rover to display rover position and system-monitoring parameters (TBD) with a 10Hz (TBR) update rate

[1] GPS data on rover and pods will be captured at all times for validation testing only; it will never be used by pod or rover, except for rover starting position known. It will be used as truth to determine accuracy.
[2] Analytical determination of pod location is an indicator that the team has developed a by hand calculation/algorithm for determining pod location to assist rover on SW-L1 path.
[3] Selectively is with respect to information such as which pods host the most valuable environmental data (based on heat map) at a specified time.
[4] Balance will be based on weighting algorithm (TBD weights) which weights ability to assist rover and value of science (value of science defined by pre-supplied heat map) to determine pod location.
[5] Online is defined as near real-time data relay between rover and ground segment.

Table 1. Project DRAGON Success Criteria

4. Functional Requirements

4.1. Functional Block Diagram

The Functional Block Diagram (FBD) in Figure 1 illustrates the connections between the rover, pods, and user. The customer-provided rover from Clearpath Robotics, includes two on-board computers, a battery, an Inertial Measurement Unit (IMU), odometer, and GPS antenna. The low-level computer will control the actuators for the rover's wheels, while the high-level computer will host the software for path optimization and deployment targeting. The rover will host the team-designed pod deployment mechanism and a customer-provided RF beacon. The only physical interaction between rover and user occurs only when the user inputs the initial conditions.

Pods will operate autonomously and will contain a RF beacon, a processor, GPS antenna, a power source, and a sensor suite (sensor types TBD). The pod idles in a low-power data collection mode and will transition into a high-power mode when transmitting, as controlled by the pod's onboard processor. The RF beacon will wirelessly transmit ranging data and environmental data to the rover. Note that data from the GPS antennas is not an input to the naviagation software. Rather, the GPS data will be stored and used in post-processing as truth to determine accuracy.

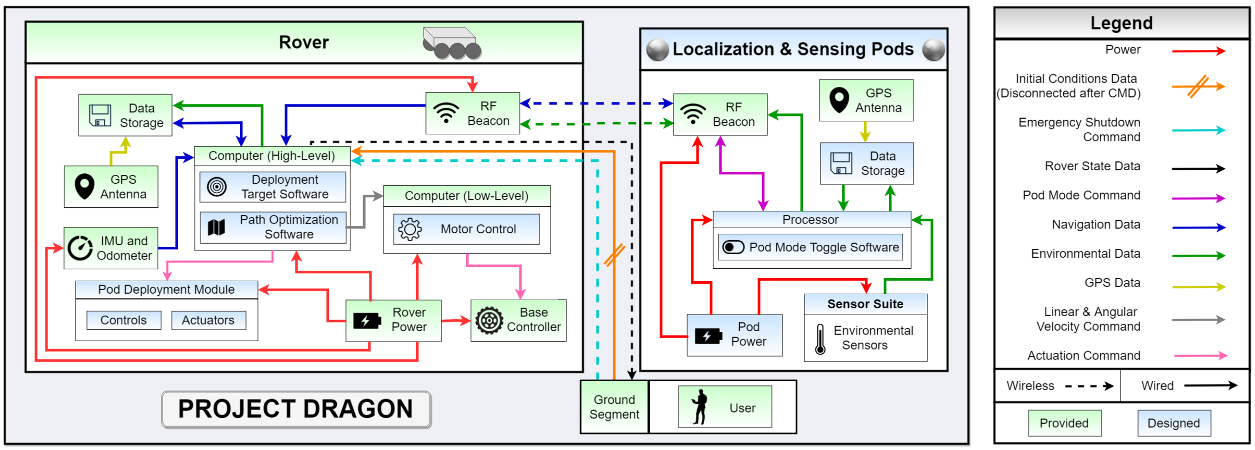

Figure 1. Functional Block Diagram (FBD)

4.2. Concept of Operations

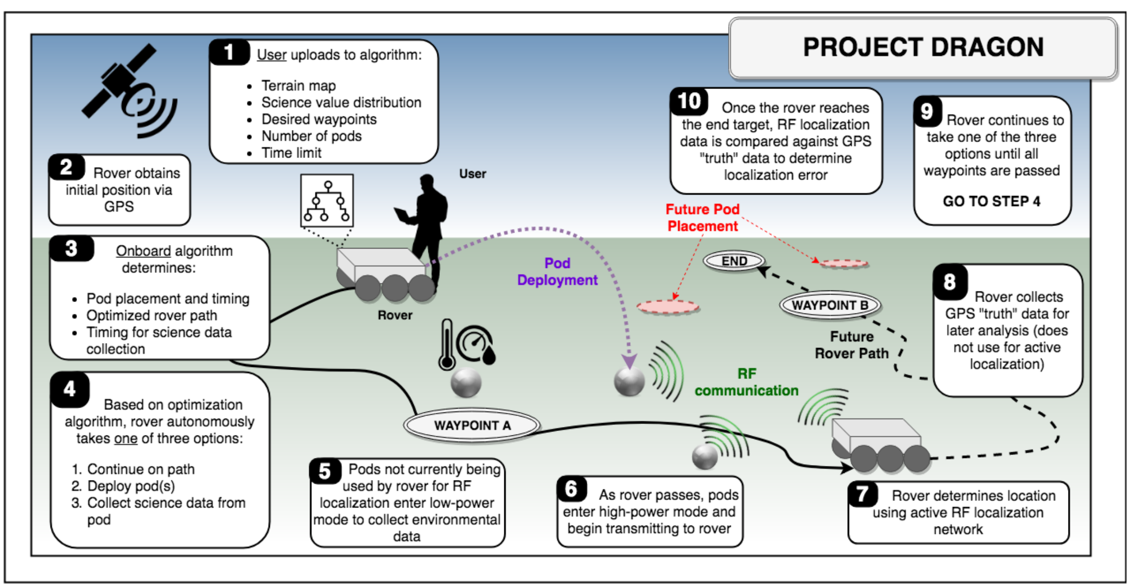

Figure 2. Concept of Operations

The CONOPS above shows how the system will operate in its test environment, one similar in size and terrain to CU Boulder South or the Business field. Using the initial conditions specified in Figure 2, the onboard rover algorithm will decide the desired path and its next steps without human intervention (see Step 4). The onboard algorithm determines if the rover should continue to drive on the path, deploy pod(s), or collect science data from previously deployed pods. This process is a loop; the rover will continue to do this step until the end of the test. As the rover traverses along the path, it uses the active RF localization network to determine its location. In addition, the rover collects GPS truth data which is used to compare against the RF positioning; GPS data is not used by the onboard navigation algorithm.

After deployment, the pods alternate between a high-power and low-power mode on a cyclical schedule. When the pods wake-up from low-power mode (i.e. hibernation) and enter high-power mode, they either transmit data science and/or positioning data to the passing rover, or briefly (timing TBD) collect environmental data and then return to low-power mode.

5. Critical Project Elements

Navigation Software

This mission centers upon enabling the rover to navigate without GPS. Using the initial inputs of the terrain map, starting location, and science distribution map, the rover's software must plan a strategy for pod deployment and path of travel. Without GPS, the rover relies on using the odometer and IMU for dead-reckoning which introduces errors when travelling distances longer than tens of meters. DRAGON will attempt to use the deployed pods to maintain accurate position information through the duration of the mission without GPS. This rests on the ability to perform real-time algorithmic state estimation. The success of the project depends on the software's ability to generate a safe rover path through terrain, pod deployment locations, and perform closed loop error correction.

Pod

The deployable pod has two responsibilities: to provide RF localization data to rovers and to collect science data. Naturally this breaks down into two electrical subgroups for sensing, collecting, and transmitting data, and a second group for integration of the customer provided RF localization module. In addition the pod requires a critical structure that must protect internal components during deployment, including impact and water resistance. If these pods are unable to perform their function after deployment both the navigation accuracy and environmental data collection will be significantly reduced. The project requires several of these pods and so their technical complexity and cost will be restricted to enable rapid affordable production.

Deployment Method

The deployment mechanism is responsible for delivering the pods to their intended long-term locations from the rover in a repeatable and safe fashion. It will also be constrained by the spatial and electrical resources of the rover. The accuracy of localization is limited by the accuracy of deployment location– if the uncertainty is too great, the rover will be unable to rely on pod's ranging data to improve its position estimate. Preferred pod deployment locations may be inaccessible to the rover– over a river , for instance– so ranged deployment is required for the project.

RF Network Communication

Mission and science objectives require that the rover regularly communicate with the deployed pods, collecting both the RF-localization signal and the environmental data recorded at the deployment site. Managing rover-pod and pod-pod communication will present logistical and technical networking issues. Both the navigation and science objectives rely on receiving regular information from the pods and will not function without it.

6. Team Skills and Interests

Critical Project Elements	Team Member(s) and Associated Skills/Interests	
Navigation	Jack Maydan	– 3D mapping experience, systems engineering
	Dawson Beatty	– Statistical learning/optimization class, Python/C/C++
	Virginia Nystrom	– APPM double major, data analysis, Python/Perl/Bash
Deployable Pod	Luke Tafur	– 2.5 years industry experience in electrical engineering
	Christian Carmack	– C/C++, Linux, digital filtering
	Ross Kloetzel	– Testing procedures, systems engineering
Deployment Method	Chris Greer	– Metalworking, machining, CAD
	Jeremy Fie	– Fabrication, construction
	Kyle Nieukirk	– Structures, fabrication, control systems
RF Network Communication	Ivan Yurkin	– RF experience, Microavionics class, EE Minor
	Amanda Siirola	– RF experience, data analysis
	Ryan Stewart	– Algorithms, Control systems, C/C++, Linux

7. Resources

Critical Project Elements	Resource/Source
Navigation	Dr. Dennis Akos (RF Signal processing knowledge), CU Business Field/CU Boulder South (Test location), Terrain and Science Distribution Maps (Customer provided), Dale Lawrence (feedback control implementation), Dr. Zoltan Sternovsky (GPS Navigation), Dr. Eric Frew (Autonomous systems/robotic feedback control), Dr. Nisar Ahmed (Vehicle systems knowledge), Dr. Brian Argrow (Vehicle systems knowledge), Dr. Chris Heckman (robotics/system modeling), Dr. Jay McMahon (Guidance, navigation, and control), Dr. Penina Axelrad (GPS navigation)
Deployable Pods	Bobby Hodgkinson (Manufacturing), ITLL instruments (Oscilliscope, Multimeter, Power Supply), Trudy Schwartz (Microprocessor knowledge), ITLL Machine Shophttps://v2.overleaf.com/8429535187bzngghydggtx (Fabrication/Prototyping), Idea Forge Machine Shop (Fabrication/Prototyping)
Deployment Method	Matt Rhode (Fabrication), Dr. Alireza Doostan (Structural and material knowledge), Dr. Carlos Felippa (Structural and material knowledge), ITLL Machine Shop (Fabrication/Prototyping), Idea Forge Machine Shop (Fabrication/Prototyping)
RF Network Communication	RF Chips, ROS nodes, Dr. Robert Marshall (Embedded Systems/Remote sensing), Trudy Schwartz (Microprocessors/Embedded systems), Steve McGuire (Embedded sytems/Advanced robotics), Tim May (Electronics), ITL Electronics Center (electronics assembly/testing), Dr. Hahn-Phuc Lee (integrated circuits development)

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