Remotely Operated and Autonomous Mapping System (ROAMS)

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Abstract— *The development of a relatively low cost mobile 3D mapping robot prototype named ROAMS (Remotely Operated and Autonomous Mappings Systems) which enables rapid generation of high resolution 3D maps of indoor/outdoor environments is presented. The Robotic system generates 3D maps using a video registered Lidar scanning system integrated with a multiple degree of freedom actuator. This vehicle is also used as a test platform for conducting studies and real-time experiments on autonomous operations. Environmental awareness sensors in combination with a long range wireless communications system is used to enable remote operation and monitoring of ROAMS. Techniques for improving the resolution and point distribution of Lidar data through the use of video images and actuator speed control are also investigated and presented.*

1. INTRODUCTION

Accurate three dimensional maps are important for applications which require geometric and visual information of environments. These applications include 3D map building for autonomous robot navigation, map generation for simulation and modeling applications, map generation of unknown/hostile terrain as well as rendering of synthetic/virtual reality 3D environments for analysis and training purposes. Robotic systems have the potential for generating these maps faster, more accurately, more conveniently and in some case more safely than manual 3D mapping methods. This is especially true for applications which require mapping large scale or hazardous/hostile environments.

While there are a number of technologies and sensors that are capable of generating 3D ranging data the most widely used sensors in the robotics field are Lidar (**Li**ght **D**etection and **R**anging) Systems. The relatively high level of accuracy, fast scanning rate, and long distance ranging capabilities of LIDAR range scanners are well suited for 3D mapping application and have made them one of the primary sensors employed in many robotic systems. These scanners are active sensors which use the emission and reception of a laser pulse to calculate direct distance measurements with Centimeter/Millimeter precision and can be used in several light conditions including absolute darkness. Most of these sensors can also measure the energy of the reflected laser pulse (reflectivity) which helps to distinguish between various components and materials in a 3D scan scene.

A number of commercially available 3D Lidar scanning systems exist, ranging in features from very fast scan rate, continuous rotation, narrow field of view 3D scanners used for autonomous robot navigation [3] to slow scan rate, very high resolution Lidar scanner used for surveying and modeling application [4]. While these 3D Lidar scanners generate excellent 3D scans they are typically very expensive.

In comparison 2D Lidar scanners cost a fraction of the price of 3D Lidar scanners and are much more affordable. Due to this, a common method used to produce low cost 3D scans is to integrate a 2D Lidar scanner onto a dynamic platform, and to use the position information of the platform to resolve the third dimension. These platforms can range from mobile platforms such as a vehicle [5] to rotary actuators that enable the rotation of the Lidar around a central Axis [1, 2]. By controlling the speed of the dynamic platform the resolution and the 3D scan rate can be controlled.

In this paper a mobile robotic platform named ROAMS (Remotely Operated and Autonomous Mapping System) is described in which a commercially available 2D Lidar (Sick LMS 200) is used for generating detailed 3D scans. The 2D Lidar is mounted onto a unique three degree of freedom actuator on top of the robotic platform which enables the ability to pan, tilt and roll the Lidar (Figure 1). This three degree of freedom actuator allows for a large amount of flexibility in the orientation of the 2D Lidar thereby enabling a single 2D Lidar scanner to be used for a variety of applications. By acquiring the simultaneous position feedback of the actuators during each 2D Lidar scan, and using the actuators to change the orientation of the Lidar, 3D scans of an environment are generated. The three degree of freedom actuated Lidar scanning system is mounted on top of the ROAMS vehicle to provide a near 360° unobstructed 3D scans.

Figure 1- Remotely Operated and Autonomous Mapping System (ROAMS)

ROAMS is outfitted with host of sensors and a long range wireless communications system enabling remote operation and monitoring with a software-based Operator Control Unit (OCU). The OCU enables mapping of large scale or human inaccessible environments by a single operator from a remote location. The robotic vehicle is also used as a test platform for conducting studies and real-time experiments on autonomous operations. The development of ROAMS is described in more detail in the following sections starting with the Hardware and Software architecture of ROAMS in Section II, operational details of the Lidar Scanning System in section III, the techniques used for improving the resolution and point distribution of 3D data in section IV and a brief description of the Operator Control Unit in section V.

2. HARDWARE AND SOFTWARE ARCHITECTURE

Vehicle Body

ROAMS utilizes the mechanical structure of a miniature ATV as the frame for the Vehicle. This frame is constructed from high tensile strength hollow steel tubes and is connected to the all terrain wheels through the use of hinges and a front and rear suspension system (Figure 2). A secondary frame constructed from T-slot 80-20 Aluminum extrusion is mounted on top of the base frame to allow for easy mounting of hardware components. The 80-20 extrusions have a unique profile that makes them rigid and provide great flexibility for mounting devices. Hardware can be conveniently mounted anywhere along the frame without the need for extra machining.

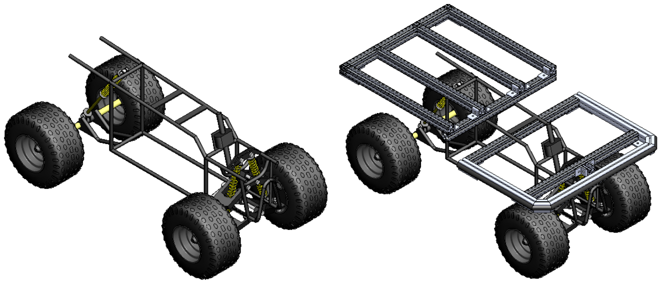


Figure 2 - CAD model of Base frame and suspension (left) and secondary 80-20 Mounting Frame (right)

Drive by wire system

The vehicle is driven using a 750W electric motor connected to the rear drive shaft using a chain and sprocket. A high torque worm gear motor is used for steering. This motor is connected to the steering shaft using a spur gear and an integrated slip clutch mechanism to disengage the motor from the steering shaft if excessive torque is applied to the steering shaft. A potentiometer connected to the steering shaft provides position feedback enabling the steering motor to be used as a high torque servo motor. Both the driving and the steering motors are controlled by a Dual channel DC motor controller. The motors and controller hardware used are inexpensive and commercially available items.

Onboard Computer and Battery power

An onboard Quad-Core computer running windows XP operating system is used for performing all the sensor data acquisition, processing, and actuator controls. This computer contains multiple ports including RS-422/RS-232 serial Ports, IEEE 1394 Firewire ports, USB 2.0 ports and an Ethernet port to enable communication with the sensors, motor controllers and other electronic components onboard ROAMS.

Twelve 12V Lead Acid batteries (connected as six 24V parallel battery banks) are used to power the computer and other onboard electronics. DC-DC converters are used for down stepping the 24V to lower voltages that are needed for low power electronics. A separate high power 37V lithium Ion battery pack is used for powering the driving and steering motors. The Vehicle can be operated for approximately 10 – 14 hours on a single charge with this battery configuration.

Onboard Sensors and wireless communications

During Remote operation of ROAMS multiple sensors are employed to provide the remote operator with 360° situational awareness. These include three wide angle video cameras (one forward looking, one rear facing and one pan tilt birds-eye view), 8 Infrared (IR) proximity sensors (4 forward looking, 4 rear facing), a GPS sensor, a 3-axis gyroscope, an acoustic microphone, and the actuated Lidar scanning system. While the vehicle is in motion the Lidar is oriented to look forward and provide 2D ranging data for obstacle detection, or to run localization algorithms such as SLAM. In its current state ROAMS is used to acquiring 3D map only while stationary.

Data is communicated to the Operator Control Unit (OCU) through the use of an 802.11 b/g Cisco Aironet 1300 wireless communication system. The onboard computer is connected to the Aironet 1300 using an Ethernet cable and a wireless antenna is used for communicating with other wireless enabled devices, such as the OCU. This system can be configured as an access point to enable communication with multiple wireless enabled devices, or is paired up with another Cisco Aironet 1300 for increased operational range and security.

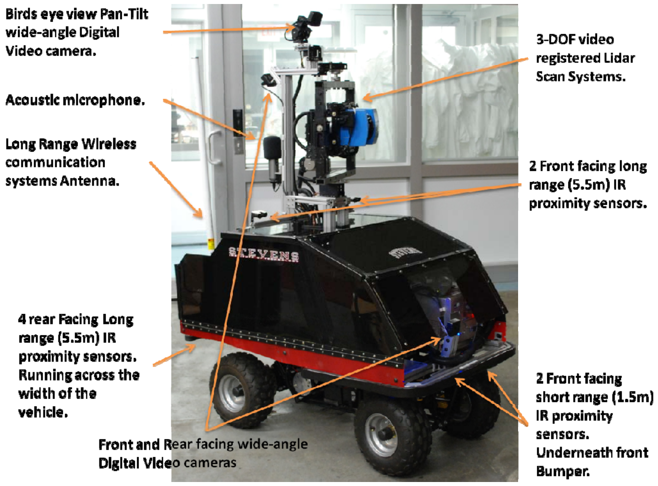


Figure 3 - Situational awareness sensors on-board ROAMS

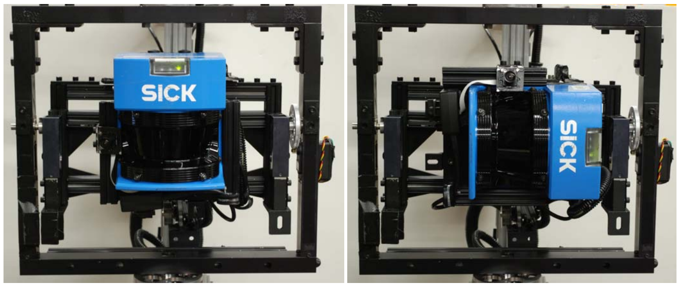
Software Architecture

All the Components on ROAMS are controlled by software components implemented using LabView software running on the onboard computer. This software comprises five individual modules which function individually, but have the ability to communicate and work co-operatively with each other. These modules are the vehicle control module (used for controlling the driving and steering motors), video and audio module (used for acquiring data from video and audio sensors), Lidar module (used for acquiring and processing data from the Lidar scanner), the servo actuator module (used for controlling the Lidar and video servo actuators), and the data acquisition module (used for acquiring data from wheel encoders, servo potentiometer and IR proximity sensors). A master controller is used for monitoring and controlling these five modules. For communication with the OCU each Module is assigned a unique TCP/IP port. Using this port the modules can transmit and receive sensor Data commands to and from the OCU.

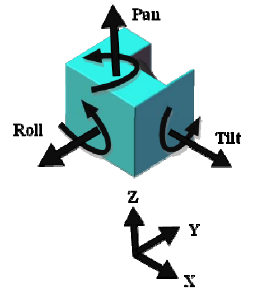
3. VIDEO REGISTERED LIDAR SCANNING SYSTEM

Lidar Scanner Acutators

The Lidar Scan actuator system utilizes three servo motors to enable orientation of the Lidar with three degree of freedom (pan, tilt, and roll). This system allows ROAMS to use a single 2D Lidar to perform tasks that usually require multiple Lidar systems. Each servo has a rotary potentiometer coupled to the rotating shaft to provide angular position feedback. The position feedbacks from these servos are used to calculate the current orientation of the Lidar and determine which part of the 3D scene is being scanned.



Horizontal Configuration Vertical Configuration



Rotational and Linear degrees of Freedom of Lidar

Figure 4 - Three Degree of Freedom Lidar Scan System

The system has two main configurations. The first is a horizontal configuration, where the roll servo is used to orient the Lidar to scan horizontally. This configuration is used for performing 2D navigation and obstacle detection while the vehicle is in motion. The Second is a vertical configuration, in which the Lidar is oriented to scan vertically. This configuration is used for performing 3D mapping operations. The roll servo is only used to switch the Lidar between these two configurations. Using a high speed RS-422 serial port, data is received from the Lidar at the maximum scan rate of 75 Hz for a 180° scan with 1° resolution (38 Hz for 0.5° resolution)

While in the horizontal configuration the Lidar is oriented to face forward using the pan servo, and the angle of elevation of the 2D Lidar scan is adjusted using the tilt servo. Different angles of elevations can be used depending on the current use of the Lidar. For Example if the Lidar is being used for obstacle Detection then the elevation angle can be lowered slightly downward, so that ground obstacles can be detected while the vehicle is in motion.

A number of different 3D Lidar scanning methods can be used as described in [1] by rotating the Lidar around different axis of rotation. The reason the pan servo was chosen, with a vertical Lidar configuration is due to the fact that this scanning method (referred to as yawing scan in [1]) allowed for the largest unobstructed field of view, and better control of the Lidar as most of the load from the mechanism is transferred axially through the shaft of the pan servo and not observed by the pan servo. When performing 3D scans the tilt servo is set to an elevation of 0° and held in that position for the duration of the scan.

Currently ROAMS is only used to perform 3D scans while stationary. 3D scans are performed by positioning the vehicle in the area of interest to be scanned, orienting the servo in the vertical configuration, and using the pan servo to scan the 2D vertical Lidar beam within the 3D scene. The position of the pan servo is used as the third dimension. The speed and rotational range of the pan servo can be adjusted depending on the resolution and field of view of the scan required. For a constant scan speed and field of view, there is a tradeoff between the resolution of the 3D scan and the time taken to produce the scan.

3D scans performed by ROAMS using this scanning method are shown in figure 5. To produce these scans ROAMS was moved to various locations around the scan environment and a 3D Lidar scan was taken at each location. GPS and gyroscope data are used for rough estimate of the vehicle position and orientation at each scan location. The scans are saved and merged, in an offline process, into one big global map. The merging process can be done manually using the GPS and gyroscope data as initial position estimates for the vehicle or automatically using a variant of the well known Iterative Closest point (ICP) algorithm [7,8]. In order to produce this global map common overlapping areas are needed between each consecutive 3D scan, and as such the scan positions are chosen such that these common areas are present.

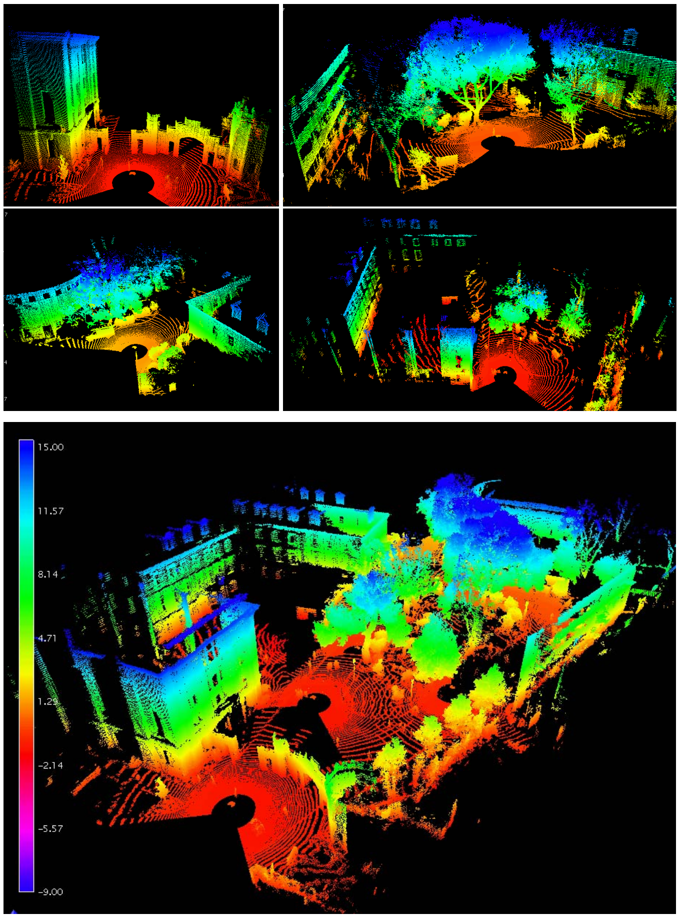
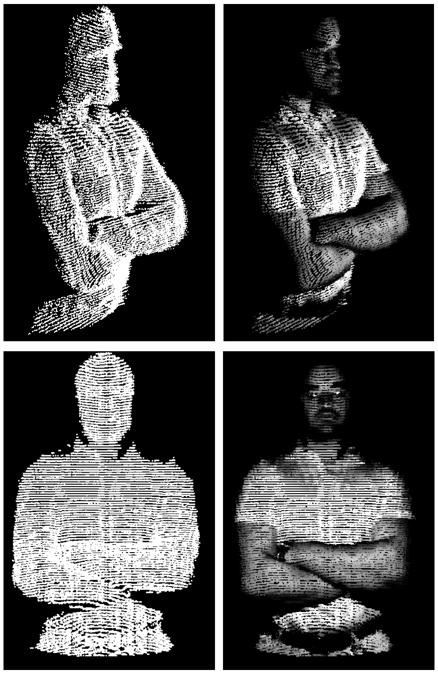


Figure 5 - 3D scans performed by ROAMS of the Stevens Institute of Technology Lower Campus area. Individual scans (top), merged global map (bottom)

The pictures in figure 5 show point clouds of merged raw Lidar distance data. The point clouds are colored to indicate the vertical distance from red (low) to blue (high). The top four point clouds show individual 3D scans at a few of the scan location, while a global map of all the scans merged together is shown in the bottom point cloud. A total of nine scan locations used to produce the map. The global map contains 13 + million points and cover and area approximately 100 meters wide and 110 meters in length.

3D Scene Digitization process

The Lidar module, servo actuator module, and the data acquisition module need to work cooperatively in order to produce a 3D scan. When performing a 3D scan the servo actuator module is used for controlling the position and velocity of the Lidar pan servo, while the data acquisition module is responsible for acquiring the azimuth angle of the Lidar from the pan servo potentiometer. Synchronization between the Lidar and the Pan servo is achieved using a similar approach to [1] in which two parallel process are used to acquire time stamped data from the Lidar and pan servo potentiometer individually. The data from these two processes is then aligned and synchronized using the timestamps in a third parallel process.



Side View

Left: Distance Only

Right: Distance and Reflectivity

Front View

Left: Distance Only

Right: Distance and Reflectivity

Figure 6 - Comparison between a 3D scan with and without reflectivity data

In addition to providing 2D distance measurements the LMS 200 Lidar can also be configured to continuously output the reflectivity values of the laser pulse (concurrently with the distance measurements)[1]. The reflectivity values can be very helpful in determining material transition and different components within a 3D scan. In addition to the material properties these reflectivity values are also dependant on the measurement distance and angle; as such they cannot be directly used for comparing scan object at different measurement distances and reflectance angles. They do however provide an additional means for distinguishing objects within a 3D scene and can also provide major improvement in the visualization of 3D point clouds. A comparison, for a 3D scan of a person, with and without the addition of reflectivity information is shown in figure 6. The person was standing approximately 1.5 meters away from the Lidar during the scan and the Lidar was configured to operate with and angular resolution of 0.5°.

A wide angle video camera mounted atop the Lidar is used to provide texture information to the Lidar Data. The center Pixel line of the camera is aligned to the 2D scan Line and used to provide texture information for each 2D scan. The corresponding RGB (Red, Green, Blue) color values for each Lidar measurement is selected, in real-time, by using the distance measurement values and the position of the camera in relation to the Lidar to perform trigonometric calculations and determine the color value of each point. A video registered 3D scan produced using this method is shown in figure 7.

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[1] This can be achieved for the LMS 200 by configuring message 77h block D (measuring mode – page 98 of [6]) to the undocumented mode 13 (0Dh) – normalized reflectivity values or 14 (0Eh) – Direct Reflectivity values. Command 20h with subcommand 2Bh can be used to request continuous range and reflectivity values. The Lidar will respond with response F5h distance and reflectivity value pairs for up to 200 measurements.

Figure 7 - Textured Indoor 3D scan (merged from 2 sparate 3D scans)

Depth Adaptive speed control

While the use of a 2D Lidar mounted on an external rotary actuator, such as the pan servo, is effective in producing 3D scans, one downside is that it produces non-uniform point distributions for different measurement distances. This non uniformity is due to the fact that for the same angular rotation, measurements points of far object will be more sparsely distributed compared to those of nearby objects (figure 8). One way to increase the measurement point density of these far objects is too decrease the rotation velocity of the external actuator. This will result in a smaller angular rotation (Θ) between each scan thereby increasing the overall point density of the entire scan. Doing this however will also unnecessarily increase the point density of nearby objects, increase the time to perform a single 3D scan, and also lead to large file sizes if the measurement data is being save for later use.

A proposed solution for this is to perform 3D Lidar scans using a variable speed rotary actuator. The speed of the actuator is controlled by the distance of the objects being measured, slowing down for measurements of far objects and speeding up for nearby objects. The objective of the variable speed actuator is to produce a more uniform distribution of points for both far and near objects than would be possible by using a constant speed actuator. While it may not be possible to obtain a perfect uniformly distributed 3D scan, this method can help to improve the general point distribution.

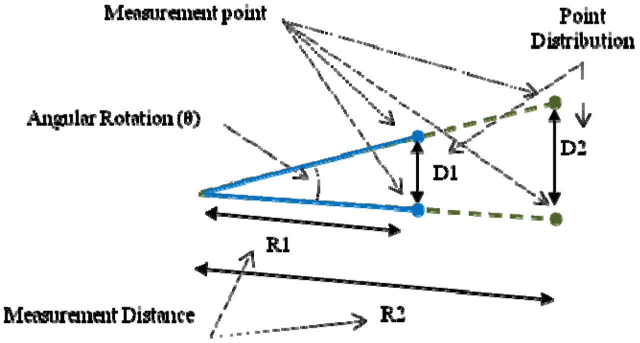

Figure 8 - Non uniformity of point distribution for different measurement distance with the same angular rotation

The methodology for the control of the actuator is composed of five functions. The first two functions involve acquiring and extracting the relevant distance measurements from the Lidar. The next function is used to calculate a scalar equivalent distance measurement from the each 2D Lidar data during a fast preliminary 3D scan. This scalar equivalent can be the maximum measured value of a 2D scan, or the mean value of all the measured values within a 2D scan. Using the scalar equivalent value for each scan position the forth function generates a velocity profile for the rotary actuator. The last function makes use of this velocity profile to perform a Feed-forward control on the angular velocity of the pan actuator to try and maintain as uniform a point distribution as possible during the 3D scan.

While this methodology can be applied to the pan servo to improve the horizontal point distribution of a 3D scan, it cannot be used to improve the vertical point distribution as this is dependent on the resolution of the Lidar scanner which is a constant for the duration of each scan.

Lidar Resolution Enhancement

The LMS 200 Lidar Scanner can be configured to run at three different scan resolutions (1°, 0.5° and 0.25°). One way to further improve the resolution of the scanner is to use information from the video camera used for texturing, which has a greater resolution then the Lidar. Using the information from the camera and making simple assumption as to the shape of the object being scanned, points in-between the Lidar scan can be interpolated to produce a higher resolution 3D scan.

The algorithm used to interpolate in between the Lidar data compares distance, reflectivity and RGB values of each pair of consecutive point in a 2D scan to make estimations as to whether these two points belong to a continuous smooth object. If it determines that they do then it will interpolate in between these two points and use the higher resolution video image to texture the interpolated data. This method has shown to work well especially for planar and smooth surfaces. The results from a scan produced using this method is shown in figure 9.

Standard resolutions scan (0.5° resolution)

Image of Scanned object

Enhanced resolutions scan (0.125° resolution)

Figure 9 - 3D scan of wooden plank with and without Lidar resolution enhancement method

4. OPERATOR CONTROL UNIT

The OCU for ROAMS is a LabView software based system which allows full remote monitoring and control capabilities to the operator of the system. This OCU can be operated from any windows based PC which meets or exceeds the minimum operating requirements for system. This allows for flexibility in the location and operation of the OCU and easy integration with existing systems without the need for additional custom hardware. There are currently two OCU configuration used for ROAMS. The first is a stationary OCU that is located at a central command center, and the second is a mobile OCU mounted on Chase ATV Vehicle (figure 11). For the mobile OCU a CF-30 Toughbook touchscreen laptop in conjunction with and additional touch screen monitor is used to run and display the OCU software. A joystick controller mounted behind the steering handles of the ATV is used for operating ROAMS.

The OCU for ROAMS was designed to be used with a touch screen PC. As such the OCU make use of a graphical user Interface (GUI) which is touch screen and user friendly (figure 10). The GUI utilizes large touch buttons, a simple layout, and a modular design that enables easy addition and removal of components from the OCU. The OCU also make use of External modules, floating pop-up panels, and tabbed pages to minimize the clutter of the main OCU window, while allowing more detailed views of sensor data and enhanced control of ROAMS systems. The External Modules and Pop-up panels are opened in new windows and as such can be moved around the screen, resized and positioned to the operators liking. Dual or large high resolution screen monitors are used to increase the screen real-estate and fully utilize the features of the OCU.

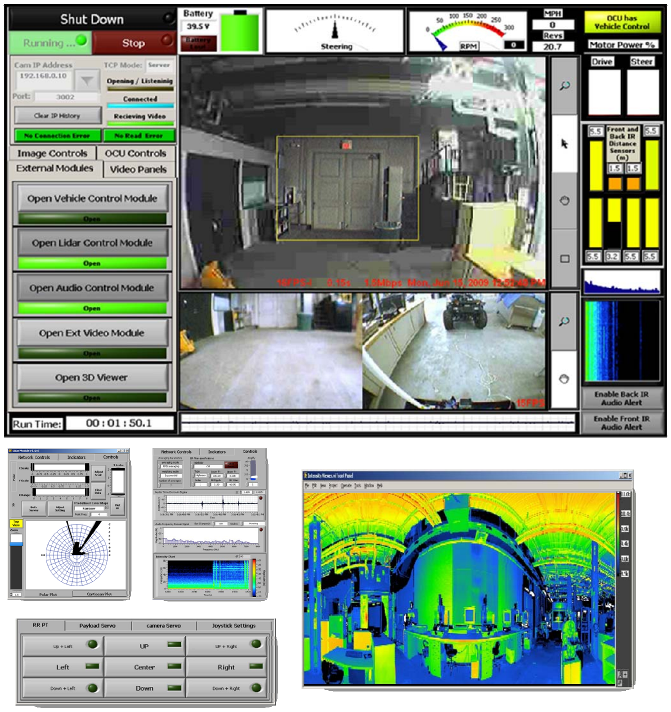

Figure 10 - Main GUI (top) and External Module and floating panels (bottom) of ROAMS OCU

Figure 11 - Mobile OCU configuration using an Electric ATV

5. CONCLUSION

The development of a mobile robotic mapping system which makes use of a unique multi-degree of freedom actuated Lidar scanning system to generate textured high resolution scans was described. The use of the multi-degree of freedom actuator enabled a single 2D Lidar scanner to perform multiple tasks that would have otherwise required multiple Lidar systems. This along with the use of inexpensive off the shelf components has resulted in a relatively low cost Remotely Operable mapping system. Remote Operation and monitoring of the robotic mapping vehicle is implemented using a software based Operator Control Unit to enable remote mapping of environments. Techniques for improving the point distribution and scanning resolution by implementing adaptive actuator speed control methods and utilizing high resolution video images were also described and shown to improve the visualization of 3D point cloud.

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