Rapid World Modelling from a Mobile Platform

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Abstract

The ability to successfully use and interact with a computerized world model is dependent on the ability to create an accurate world model. The goal of this project was to develop a prototype system to remotely deploy sensors into a workspace, collect surface information, and rapidly build an accurate world model of that workspace. A key consideration was that the workspace areas are typically hazardous environments, where it is difficult or impossible for humans to enter. Therefore, the system needed to be fully remote, with no external connections.

To accomplish this goal, an electric, mobile platform with battery power sufficient for both the platform and sensor electronics was procured and 3D range sensors were deployed on the platform to capture surface data within the workspace. A radio Ethernet connection was used to provide communications to the vehicle and all on-board electronics. Video from on-board cameras was also transmitted to the base station and used to teleoperate the vehicle. Range data generated by the on-board 3D sensors was transformed into surface maps, or models.

Registering the sensor location to a consistent reference frame as the platform moved through the workspace allowed construction of a detailed 3D world model of the extended workspace.

1. Introduction

Under the Department of Energy's (DOE) Robotics Technology Development Program, both Oak Ridge National Laboratory (ORNL) and Sandia National Laboratories (SNL) have been working for the past several years with commercial vendors and universities funded under the DOE University Robotics Program to define and build a mobile mapping system capable of large scale three dimensional mapping of unstructured environments [1]. Figure 1 shows the integrated Mobile Mapping System that was built under this program. For the past

two years, ORNL has taken the lead in program management and system integration while SNL has focused on rapid world modeling technology [2] and on building a portable structured light mapping sensor and supporting electronics. Other efforts that have been leveraged for this project include the invention and development of a dual differential drive electric vehicle by the University of Michigan and HelpMate Robotics, the development of a Coherent FM laser radar by Coleman Research Corp., and the development of a visualization and modeling software package by Mechanical Technology Incorporated under a contract managed by the DOE's Morgantown Energy Technology Center.

Figure 1. Mobile Mapping System

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Research into many aspects of both video and range image processing is being carried out by the Universities of Tennessee and Florida under the DOE University Robotics Program and kernels of functionality are planned for integration into the overall project at a later date.

2. System Description

2.1 Vehicle

The OmniMate™ vehicle was designed under a Small Business Innovative Research contract from DOE in 1993 by Transitions Research Corp. (since renamed to HelpMate Robotics) and the University of Michigan Advanced Technology Laboratory. Borenstein describes the vehicle's complete kinematics and controls in [3]. The vehicle is based on two LABMATE™ vehicles which are fixed to a rigid platform with a compliant linkage and rotary joints. The result is a 4 degree-of-freedom, dual differential drive vehicle with a compliant linkage which allows for internal correction of dead reckoning errors [4].

As shown in Figure 2, the vehicle's two independent drive units or "trucks" are able to rotate about a vertical shaft connected to the vehicle body. Each truck comprises two drive motors, along with their respective reduction gears, encoders, and drive wheels. Each pair of drive wheels is located on a common axis and forms a differential drive system capable of moving forward, backward, and rotating—simply by controlling the velocities of the drive wheels. Each truck also holds four castors for stability when traveling sideways. Mechanical compliance is implemented by means of a linear bearing that allows relative motion between the front and rear truck.

Figure 2. Diagram of OmniMate platform showing compliant linkage and rotary encoders.

Each truck is powered by a separate battery system and a third battery system powers all on-board electronics. The use of separate battery systems allows for independent planning of vehicle locomotion and electronics system usage. While not yet experimentally verified, it is estimated that both the vehicle and the electronics can operate up to 12 hours continuously between battery charges.

2.2 Communications

A commercial, radio frequency (RF) Ethernet bridge provides the main communication link between the base station and the mobile platform. This link carries all normal command, status and data exchanges. Serial (RS232) communication to the subsystems on the platform is achieved using a terminal server connected to the platform end of the Ethernet bridge.

A separate RF video transmitter broadcasts a video signal from the vehicle to the base station. A third RF link is available to transmit an emergency stop signal from the base station to the platform.

All RF links are FCC Part 15 compliant broadcasting at < 100 milliwatts. The Ethernet bridge operates in the 2.4 GHz frequency range. The video and emergency stop links broadcast in the 915 MHz range.

2.3 Computing Systems

The computing resources used for this system are fairly common. Figure 3 shows the arrangement and interconnections of all systems. On-board (mobile) computers include an IBM compatible 486 PC to control the vehicle. Communications to the vehicle computer are performed through a serial protocol using a UNIX socket mechanism. The vehicle interprets asynchronous commands and responds to status requests. Its local real-time control system is designed to be stable at all times, so no real-time communications with it are necessary. A separate, radio controlled, emergency power off switch is capable of interrupting vehicle wheel power remotely in an emergency situation. The vehicle also contains six perimeter contact switches which interrupt vehicle wheel power in the event of a collision.

Figure 3. Mobile Mapping Computers

The Coleman coherent laser radar is controlled by an IBM compatible PC running OS/2, the Coleman radar control application, and a software package for remote operation of any OS/2 native application. This computer is shock mounted with laser power supplies and optical switching equipment in a 19" equipment rack mounted on the vehicle platform. (See Figure 1.) At the base station, a separate PC, also running OS/2, is used to control the Coleman laser system for collection of high density, high precision range images, and for system registration.

A 100 MHz, SGI Indigo 2 workstation, with a Galileo Video board, serves as the base station for the system. This computer provides live video capture and display and runs the user interface application for teleoperation of the vehicle and control of the Sandia sensor system. It runs the user interface applications and performs the video capture, image processing, and range computations for the Sandia sensor system and the modeling code that creates surface models from the range data generated by all of the sensors. Data visualization applications also run on the SGI.

2.4 3D Sensors

2.4.1 Coleman Coherent Laser Radar

The Coleman Research Corp. laser radar is a prototype frequency modulated, continuous wave, coherent laser radar (CLR) that was developed under a DOE funded Small Business, Innovative Research program by Coleman Research Corp. of Springfield, VA [5]. The radar is a very high precision range measuring device with a wide field of view, and a programmable scan pattern. It is capable of taking large data sets and can operate without operator intervention after being started.

In tests at ORNL, the system has been shown to be range accurate to about 10 micrometers. The current system has a 2-15 M range. Field of view is ± 270 deg. in azimuth, ± 60 deg. in elevation. It is completely programmable, so that a scan of any area within its field of view at any angular resolution that is desired (up to .5 arc second) can be created. The system can also be programmed to take range measurements at a predefined set of azimuth and elevation angles.

2.4.2 Sandia Structured Light and Video Ranging System

The second major sensor on the Mobile Mapping System is a Sandia supplied 3D range sensor system. The Sandia system serves three main purposes: first, it provides the video signal and control (camera selection and pointing) for teleoperation of the vehicle; second, it allows identification, measurement and then utilization of reference points for sensor registration; third, it provides an alternate 3D surface mapping capability.

The mobile system hardware consists of an electronics package and two pan & tilt units (one mounted at each end of the platform) which carry a pair of color

video "driving" cameras, a black and white video "structured light" camera, and a plane laser. The electronics package includes the RF Ethernet and video links, the terminal server, a video switch, RS232 controllable relays, camera control units, pan & tilt control units and power supplies. The user interface on the SGI base station allows the operator to select the video source, command and query the pan & tilt units and activate and deactivate the laser.

This system provides both structured lighting and stereo vision range measuring capabilities. Both capabilities rely on the calibration of the pan & tilt units and their attached camera or laser. Calibration allows the system to determine the mathematical equation for the line of sight from any pixel in an image or for the plane of the laser given the units pan and tilt angles. To generate structured light surface data, the system points the camera at the surface of interest. The laser is swept across the camera's field of view. The system grabs video frames and processes the images to locate those pixels illuminated by the reflection of the laser beam from the surface. The intersection of the line of sight from these pixels and the laser plane produces the location of points on the scanned surface. Unlike most laser range imaging sensors that provide a regularly spaced range image, the output of this structured lighting sensor is a string of irregularly spaced points, with little implicit connectivity.

The Sandia sensor system also has an interactive stereo video targeting capability that allows the user to quickly determine the position of any target in the workspace. The operator identifies corresponding features in images from any pair of cameras. The system computes the intersection of the lines of sight defined by the feature to determine its location. This 3D measurement capability is used to locate reference points for registering the sensor at future platform locations and for defining areas to be scanned by the structured light system.

In the lab, range accuracy was measured to 1/4 inch at 10 to 15 feet. On the platform, tests show an accuracy to 1 inch at 20 to 30 feet.

3 System Operation

3.1 Driving the Vehicle

The mobile mapping system is a teleoperated system with capability for future autonomous operation. The current *modus operandi* is for the user to drive the vehicle from a graphical user interface while watching one of several possible video camera signals generated on the vehicle. The user is also supplied with a graphical representation of the mapped area relative to the vehicle, and given an update of the vehicle position relative to the mapped area once per second.

The driving GUI is shown in Figure 4. It provides battery system voltage levels, position and orientation relative to the session starting point, velocity control, and mouse based translation and rotation controls.

Figure 4. Mobile Mapper Driving GUI

3.2 Data Collection

The mobile mapping system was deployed in the Robotics Technology Assessment Facility (RTAF), a highbay facility at Oak Ridge National Laboratory. The platform was remotely driven from a control console located in an adjoining room. The video cameras at the front and back of the vehicle were used to provide visual feedback for manual driving.

The test area was on the south end of the highbay, in a space about 65 feet wide, 45 feet deep, and 60 feet high. The main floor area was basically free of obstruction. The walls, however, were rich with features: beams, piping, ducts and trays, and various openings. There were a number of items lining the walls. Figure 5 shows a photo of the south wall of the RTAF.

Figure 5. Photo of RTAF South Wall

The CLR range sensor was placed at a central location and data was taken over the three end walls. A series of 7 data sets were collected, each approximately a 35 by 45 degree field of view, with 280 by 280 points per scan. This corresponds to roughly a data point every 3/4 inch.

Registration of the CLR was accomplished by scanning 4 1" steel tooling balls within the workspace. The location of these balls were arbitrarily but conveniently chosen to define the world coordinate origin. Once the location of the target spheres are known relative to the sensor, an inverse transform is created to output the CLR data relative to the coordinate frame of the target spheres.

Data was collected from the Sandia structured lighting sensor in the south west corner of the RTAF. 35 scans were taken to cover the corner area; approximately 60 linear feet of wall space. Data density was about 550 points per scan corresponding to roughly 3 inch spacing at the wall.

A method similar to that used by the CLR was used to register the Sandia range sensor. However, the targets used for registration could be selected from targets identified and located from previous sensor locations, allowing the platform to maintain registration even as the platform moves out of view of the original known targets.

3.3 Creating the Model

Each 3D range sensor provides a list of range values of detected surface points scattered over the scan area. Given the position and orientation of the sensor, this data is transformed into the x-y-z coordinate system of the world model (see the upper left quarter of Figure 6.). It is often necessary to filter the data to reduce data counts, smooth noisy data, and eliminate spurious errors that manage to show up in all sensor data.

Figure 6. Range image conversion process

At this point, the x-y-z points are used to form a triangulated surface, or a series of triangles (see the upper right quarter of Figure 6.). This process may be trivial where data is collected in a uniform grid by simply connecting neighboring points. However, alternative methods are often needed to triangulate edited or filtered data, and particularly non-gridded data such as that returned by the structured lighting system. Even with pre-filtering, the resulting triangle list can be quite large; often too large to be useful in the world model. A design goal of the world model is to maintain a total display size below 100,000 polygons, to maintain real-time update rates. Post-filtering can be used to reduce the triangle count (see lower right quarter of Figure 6.). The desire is to maintain

data where surfaces are changing rapidly, while combining co-planar triangles on flat surfaces. The resulting surface model, composed of a series of connected triangles, is ready with minimal reformatting to be placed in the formal graphical world model renderer/simulator.

4 Results and Discussion

A challenge for all untethered remote systems is communication. The RF Ethernet bridge was very successful, allowing the use of hardware and software already designed to operate over a standard network. The RF bridge operates at about 1/5 the bandwidth of the direct wire connection. Some overloading of the network was experienced, due to external traffic. However, the system communications never exceeded the bandwidth.

RF video transmission was workable, but less successful. In a tight environment, such as in-doors, video signals are prone to interference; ghosting, color shifting, etc.. Interference was also noted from other RF transmitters; although they were broadcasting in lower bandwidths, bleeding due to harmonics were showing up.

As for modelling, the raw CLR data point count for the seven separate scans added up to just over a half million points. Simple connectivity to form a surface would give more than one million triangles; well over the desired limit. To create a usable model of the CLR data, the three step process mentioned above was used. The data was pre-filtered, using a spatial filter to eliminate neighbors below 2 inches. Some manual editing was used to eliminate obvious bad data points. The upper left of Figure 6 is a view of the raw data points, filtered from 78,400 to 12,489 points. Triangulation was done based on Delaunay triangulation [6]. Post data reduction was done using a decimation approach [7] to eliminate polygons. The model generated from the CLR data has a 90% data reduction. Figure 7 shows multiple patches of the world model created from the CLR scans, integrated into one composite model. Total polygon count in this model is about 90,000 polygons.

5. Future Directions

The mobile mapping system was designed to support a future automated driving capability. The world model will be used to dynamically update a path planning function. Automatic computation of the best next view of the workspace has already been demonstrated by University of Tennessee researchers and is planned for integration soon.

Greater data reduction is needed, along with better automation in segmentation. Work is ongoing at the labs and universities in creating models by fitting simple to complex models directly to the raw data points. This technique is aimed at creating models of man-made objects (pipes, tanks, walls, floors, etc.) that can be readily modeled with simple geometry. Data reduction in excess of 100 to 1 is anticipated. Work at the University of Florida in this area is showing promise for automatic

geometry fitting to raw range data and may be incorporated in a future version of the mapping system software.

6. Conclusion

A mobile mapping system has been developed and deployed. 3D range sensors are used to collect surface data. This data is transformed into surface models of the scanned areas. The mobile platform allows the sensors to be placed so multiple scans can be taken over a large facility. These data sets are combined to form a complete map of the target facility. The geometric map is the beginning of a full characterization of a site for further processing.

Figure 7. Composite 3D map of RTAF

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