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An Integrated Robotic Multi-Modal Range Sensing System

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Abstract *– Creating 3-D surface representation of large objects or wide working areas is a tedious and error-prone process using the currently available sensor technologies. The primary problem comes from the fact that laser range sensors allow to capture at most one line of points from a given position and orientation, and stereo vision systems accuracy is dependent upon the initial camera calibration, the extraction of features, and the matching of features. When the registration process is not properly controlled, registration errors tend to significantly degrade the accuracy of measurements, which is revealed to be critical in telerobotic operations where occupancy models are built directly from these range measurements.*

The reliability of range measurements within a singular range sensor technique can drastically distort the registration process, especially within environments unsuitable for the system. Instead of utilizing a single range sensor, we adopt the use of a multi-modal system allowing diverse modes of range sensing techniques to complement each other in the hope that one system's strength could be used to compensate for another system's weakness. Using a mixture of active and passive range sensing techniques, both giving dense and sparse datasets, this multi-modal range sensing system is integrated seamlessly with minimal processing overhead and optimal workspace.

Keywords *– Range measurements; robotic sensing systems; data fusion; multi-modal data collection.*

I. INTRODUCTION

Workspaces in real world telerobotics applications are three-dimensional and complex. Therefore the acquisition of range data from many different viewpoints is required to properly construct an adequate occupancy model. This requirement for a full 3-D dataset can be met by mounting range sensors on a precise robotic arm to acquire data from multiple positions and orientations. However, the acquisition of range data on cluttered workspaces tends to be a complex and tedious task, since most laser range finders only allow making measurements along either a single point, or a line, and stereo vision systems require the use of complex calibration, feature extraction, and feature matching algorithms.

On the other hand, original equipment manufacturer (OEM) solutions provided with typical robotic arms, laser range finders, and stereovision systems are separate entities. This leads to the operator of the system to manoeuvre the robotic arm to the desired position using the provided robot OEM tools, acquiring the required data from the laser range finder using the other set of supplied tools, and then acquiring the images required for the stereo vision system using yet another set of tools, and then repeating the process for each successive position and orientation required to complete the 3-D dataset. In most vendor equipment the availability of system integration is non-existent, which reduces or inconveniences the possibility of collaborative and facilitated automation either for the purpose of calibration or acquisition.

This iterative and tedious manual process leads to errors in registration of the data through human faults and is submitted to a lack of repeatability. Since the data acquisition process takes a significant amount of time, the acquisition environment is more susceptible to perturbations. Moreover, such a manually operated system can hardly find an application in industrial processes where efficiency is a critical issue. An automated solution is therefore desired to increase productivity, repeatability, precision, and to decrease the data acquisition time.

Most systems, which have received much interest in academia and industry, have used only uni-modal range data acquisition systems. The most prominent of these, is the Mars Pathfinder, which used a stereovision system [1]. Additional systems are available, but they are used to provide imaging of historical items and places [2][3], or for medical imaging (MRI, PET, CT-Scan).

Others have successfully created multi-modal systems based upon various technologies. A laser range finder and a sonar/acoustic sensing system have been integrated into a sensing system [4][5]. The success of these multi-modal systems is dependent upon an environment that is essentially two-dimensional. For example if the system is scanning a chair with legs, there exists no mechanism that will match the data collected by the sonar and the laser range finder systems since the laser will only pick up the legs, but the sonar will pick up the rest of the structure, and hence the chair will not be properly rendered in the resulting merged data set.

In [5] and [6], a laser range finder is merged with an omni-directional stereovision system. In contrast to the multi-modal range sensing systems presented in [4] and [5], the problem of merging different datasets acquired through various range sensing technologies is defined by Miura *et al.*[6]. Miura *et al.* propose that the classification of each range sensing modality, based upon the strengths, weaknesses, and limitations of that modality, is performed through creation of probabilistic grids, which also allow the merging of the various datasets.

Most of the research work performed on multi-modal sensing is concerned with mobile robots. The present work is directed toward the development of semi-autonomous telemanipulator systems operating in complex hazardous environments. This research environment imposes different constraints, but can still benefit from the use of multi-modal sensing systems to ensure the safety of the robotic system and its operator.

In the proposed system, it is possible to collect range measurements in three distinctly different ways: directly from the laser range finder, from stereovision, and using the structured light provided by the laser range finder and one of the cameras used in the stereo vision system. This test bed therefore has the capability of providing four different sets of data (laser range finder data, stereovision data, left view structured light data, and right view structured light data), mutually registered to a common reference frame. Under specific working conditions, some of the sensors should provide more reliable measurements than others, for example if a lighting source were not present, stereovision systems would not yield good results. It is therefore important to develop mechanisms that will automatically emphasize those reliable measurements to build a 3D representation.

For the process of collecting data, this paper presents the implementation of a prototype that has been developed to automate the process of multi-modal range measurement collection by integrating a high-end one degree-of-freedom laser range finder and a stereo camera system with a seven degree-of-freedom serial robotic manipulator. The multi-modal range sensing system provides the necessary test bed to conduct data collection to research possible solutions to the sensor measurements emphasis problem.

II. System Components

A. Robotic Arm

The robotic arm employed in the system is a F3 manipulator from CRS Robotics [7] that has 6 revolute joints, and is mounted upon a CRS 2 meter track [8]. This 7 degree-of-freedom (DOF) serial robotic arm is controlled via a digital programmable controller, the CRS C500C [9]. The controller has several communications methods, of which the RS-232 asynchronous link is the most desirable, since an additional communications adaptor is not required on the external controlling computer.

The software supplied by CRS, Robcomm3, provides a compiler for the RAPL-3 language [10], so that customized applications can be programmed for controlling the robotic arm and track. The RAPL-3, in particular interest for this application, provides a method for accepting user input over the communication link, and a method for the simultaneous control of all joints that the robot possesses.

B. Laser Range Finder

The laser range finder employed is a Jupiter laser line scanner manufactured by Servo-Robot Inc. [11] that exploits the well-known synchronized triangulation technology developed at NRC [12]. This range finder is able to acquire 256 or 512 points per scan on a single line. The Servo-Robot Cami-Box [13] is used to control the Jupiter laser line scanner and also offers a RS-232 asynchronous link that connects to an external interface.

This sensor has been selected for its relatively large scan range that goes up to 1 meter, its high resolution and its compactness. Very few commercial range finders offer a sufficient scan range combined with a resolution that is suitable for the application considered [14][15][16] while representing a light payload for the manipulator.

The software application developed by Servo-Robot, WinUser, has a functionality that allows the acquisition of raw range profiles, as well as the setting of the various parameters of the Jupiter scanner to suit specific applications. Range data is normally saved to a proprietary file format (.3dx).

However, our previous experiments with this software revealed to be inefficient as the operator had to intervene after each scan to manually save the data acquired. This motivated the development of a new interface based on the RS-232 link to directly and automatically control the sensor, transfer the range data from the internal controller memory and save this information to a more suitable format.

C. Stereovision System

In addition to the laser range finder, we have constructed a chassis that supports, not only the laser range finder, but also a pair of Sony XC-999 CCD cameras, which is a key component of the VRex CAM-3000C product [17]. To synchronize stereovision image acquisition, the use of the VRex VRMUX2N is coupled to a Matrox Orion video card permitting real-time image sensing.

The Sony XC-999 CCD cameras are lightweight and require little power to operate. Since the robotic arm is restricted by the mass of its end-effector, these two cameras can be successfully integrated with the option of repositioning the baseline between the two cameras. The camera control, accomplished by the VRex VRMUX2N unit, ensures reasonably simultaneous stereo image acquisition within a period of an internal or provided external clock source [17]. This eliminates the need of constructing software to synchronization between individual cameras and eases the processing required for automation purposes. To reduce equipment cost and overhead, the VRex VRMUX2N provides a multiplexed single interlaced video feed of both stereovision cameras.

Lastly, for video and image processing, a Matrox Orion video frame grabber effortlessly de-interlaces multiplexed feed using its on-board processor and alleviating resource consumption for other real-time processes.

III. SYSTEM DESIGN

A. *Hardware*

The integrated system uses an Intel-based computer running Windows 2000 that is interfaced with both the F3 manipulator controller and the Jupiter scanner controller via two RS-232 asynchronous links as shown in Fig. 1. The stereovision system is connected via BNC coax cable to the video acquisition card installed in the computer. The laser range finder and the stereovision cameras are mounted on the end-effector of the robotic arm with a dedicated bracket as shown in Fig. 2. This configuration allows synchronization and tracking with high precision of the displacement of the sensor. This in turn allows the ability to request a scan of a profile when the desired pose is reached, and to download, display and save the range measurements in the desired format and location for further processing by modeling software.

Using the OEM supplied software, the robot had to be moved to the desired location through the use of the robot's software interface, and then using the laser range finder's software, the range data was acquired and saved to a separate file. This meant that for a scan of N lines, N different positions were manually calculated by the operator, and N different files were produced following operator's intervention. Additionally to this time consuming process, the files containing the laser line range data were in a proprietary format, unsuitable for direct fusion into a 3-D occupancy model using other software developed in our laboratory.

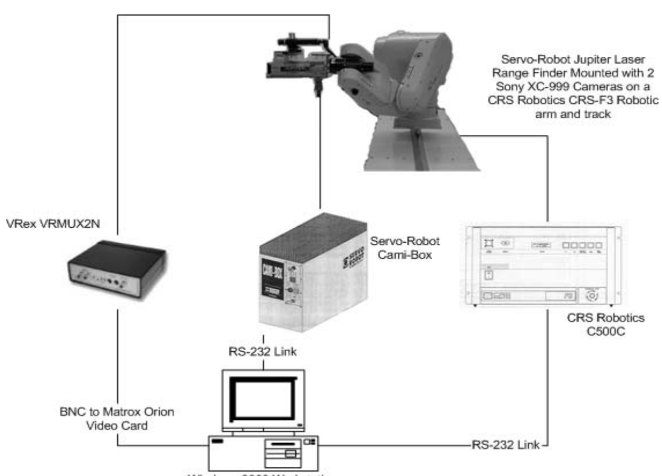

Fig. 1. Diagram of the integrated system.

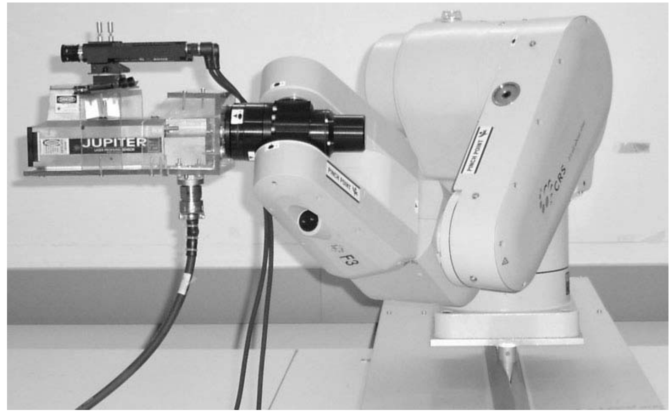

Fig. 2. The multi-modal range sensing system.

B. *Software*

To overcome these limitations, a custom interface was designed to integrate the functionalities of the robot arm, and the laser range finder. Using a custom developed RAPL-3 application that accepts the destination joint positions as input to control the robot arm, as well as a modified inverse kinematics solution inspired from [18] for this specific 7-DOFs manipulator, the robot controlling module of the application was developed.

The module to control the laser range finder relies on low level internal commands provided by the manufacturer to interact with the Cami-box controller [19]. Of particular interest for this application was the implementation of the commands to enable and disable the laser, to activate the acquisition of the data using the scan command and to download the information stored in the sensor's controller memory.

Prior to any use of the robotic multi-modal system for the purpose of acquisition, calibration of the range sensing sensors is required. The calibration mechanism of the stereovision system allows the operator to customize the baseline of the stereovision system for different applications. A second calibration is also required between the laser range finder and the stereovision system to ensure that both systems have correlating sampling points [20].

To facilitate the required calibration processes, a graphical interface was implemented to handle both stereovision and multi-modal calibration. Coupled with robot functionality, the Matrox Image Library (MIL) [21][22], and the Open Computer Vision Library (OpenCV) [23] architecture a calibration application was built to automate this process in an accessible pre-allocated robot workspace.

The MIL provides direct access to the Matrox Orion processor performing basic image processing, such as de-multiplexing functionality that is required to separate the interlaced images. From the segregated left and right images of the stereovision system, OpenCV provides the necessary intrinsic camera calibration [24] and dense stereovision system disparity algorithm [25]. In tandem, we calibrate between the stereovision system and the laser range finder using the multi-modal calibration approach proposed in [20].

Two separate user-friendly graphical interfaces (GUI) were designed. The first manages the operation of the robot arm and the laser range finder as shown in Fig. 3, and the second manages the data acquisition and calibration of the multi-modal system incorporating the laser range finder and the stereovision system with the robotic system as shown in Fig. 4. Both GUIs use the same set of libraries developed for controlling the robotic system, the laser range finder and the stereovision system.

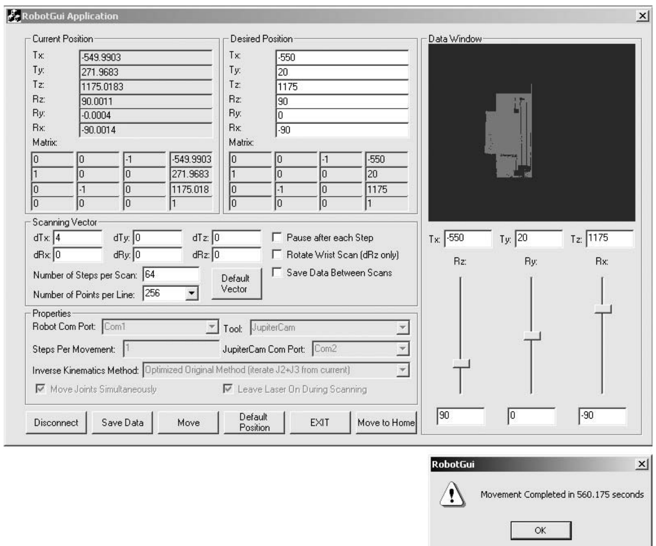

Fig. 3. Robot and laser control application GUI.

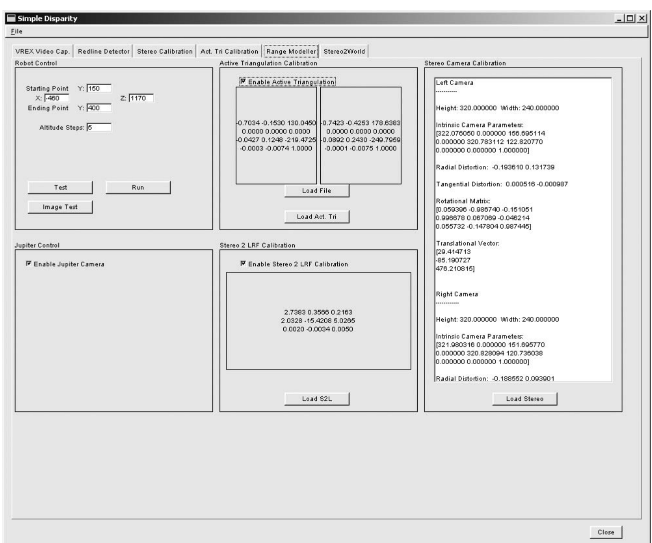

Fig. 4. Multi-modal calibration GUI.

Using these interfaces, the operator now only has to specify the main parameters for the scan that include the starting position and orientation encoded in a homogeneous transformation matrix (S), a vector defining the magnitude of the steps of the sensor along each direction that is encoded in a homogeneous transformation matrix (D), and the number of steps for the acquisition of the data (N). Using this limited set of parameters, the operator can select the desired resolution and size of the workspace to be measured. The data collected from all positions and orientations visited along the scanning trajectory are then saved to a single file to facilitate further processing and minimize errors. The user may also select to constrict the robot to move each of its joints one at a time, to turn off the laser range finder after each acquisition, and to acquire a scan through the rotation of the last degree of mobility only, therefore offering various scanning modes.

C. *Integrated system's operation*

Assuming that the integrated robotic system and the multi-modal range sensor have been appropriately calibrated, a typical acquisition sequence using the parameters set by the operator then results in the following steps:

1. The current scan position (P) is determined by the starting transformation matrix (S), and the step transformation matrix (D) multiplied by itself n times, where n represents the current step number and is between 0 and N, such as: $P=SD^n$
2. Once the scan position is computed, the robot inverse kinematics solution is used to generate the 7 joint values.
3. The robot control module then moves each of the joints (sequentially or simultaneously) to their respective angular position.
4. Once the robot is finished moving, the line of data is acquired. The range data from the multi-modal range sensing system is kept in a temporary memory with the corresponding pose of the sensor.
5. Steps 1 to 4 are repeated until n=N.
6. Once the scanning trajectory is complete, the operator clicks on a button on the graphical interface to automatically save the entire acquired data to a specified file that is compatible with our 3D modeling software.

IV. Experimental Results

Originally, the time to acquire 64 lines of data per viewing area from a series of 3 different viewing areas using the OEM provided set of tools, excluding merging the data into one viable set of data points, was on the order of a day [26]. Repeatability was low, due to the manual driving of the robotic arm by using the supplied command line interface, or the pendant tool. Important loss of precision in the registration of the position and orientation parameters was occurring as a consequence of numerous manipulations.

Fig. 5. Mock-up chair.

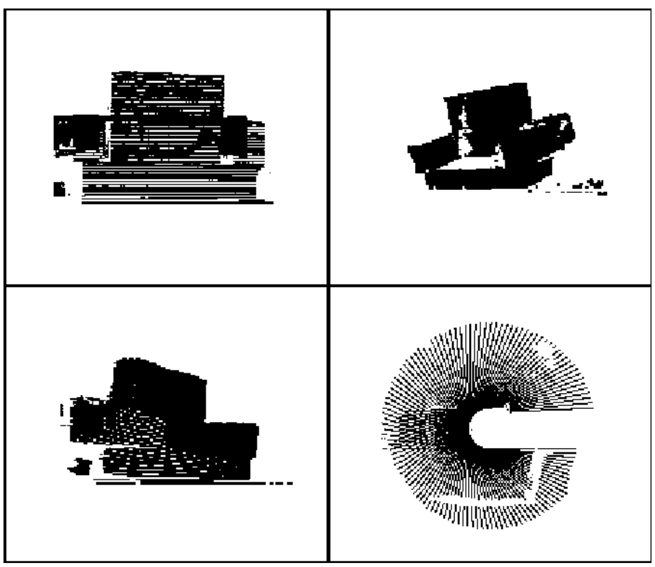

Fig. 6. Laser range finder resulting scans of mock-up chair

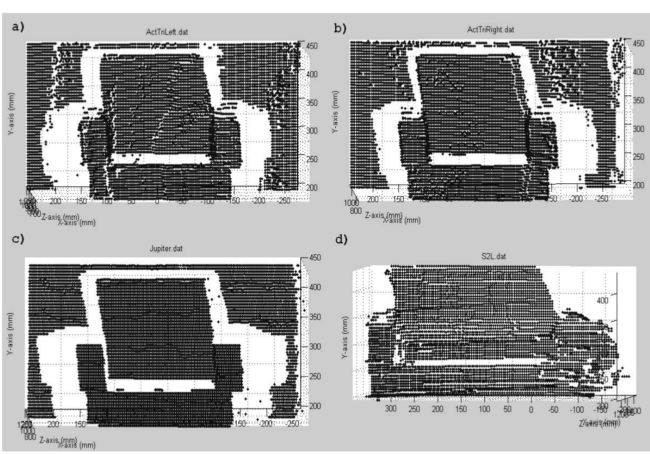

Fig. 7. Scans of the mock-up chair: a) active triangulation using left camera, b) active triangulation using right camera, c) laser range finder, and d) stereovision.

Using a former prototype of the robotic sensing system that only used the laser range finder, the time to acquire the 64 lines of data per viewing area from 3 different viewing areas when the robot joints were moved individually, and the laser was turned off after each line of acquisition was reduced to about 3 hours [27]. Using the latest version of the integrated multi-modal acquisition setup, the time to acquire the same 64 lines of data per viewing area from 3 different viewing areas is now reduced to about 30 minutes. Precision of the fusion of the multiple lines of range data is ensured by using maximal precision in the registration parameters of the system as provided by the robotic arm. Repeatability is also much improved due to the fact that sensor displacements are now fully programmed and take advantage of the precision of the integrated computer controlled solution. Moreover, four complementary streams of range data are now made available from a single scanning procedure.

Data visualization is currently accomplished through both a Windows GUI and Matlab scripts to present the 3D distribution of raw measurements. A sample of range data points collected from a mock-up chair, shown in Fig. 5, using only the laser range finder and following different scanning patterns is presented in Fig. 6. The two top images, and the bottom left image correspond to positions and orientations of the sensor using a rectilinear scanning pattern from various viewpoints, and the bottom right image corresponds to a circular scanning pattern. We can observe the quality of the mapping and the limited number of outliers that are collected by viewing the data presented in all four images. This is critical in ensuring a proper modeling of complex surfaces on which a telemanipulator will have to interact.

Experimentation has also been conducted to evaluate the potential quality of the integrated multi-modal system. The same data visualization process is used in Fig. 7, which shows four images of the mock-up chair, presented in Fig. 5, against a wall background. Although the sources of all these datasets are from different subsystems within the multi-modal system, they have been transformed such that the views are from the same perspective using the predetermined calibration [20]. This experimentation demonstrates that a proper calibration and operation of the multi-modal acquisition system is achieved.

V. Conclusions And Future Work

The worth of an automated multi-modal range data acquisition system consisting of a integrated robotic arm with a laser range finder and stereovision system has been demonstrated primarily through the improvement of the acquisition time. Additionally, since there is no intervention of a human operator between the acquisitions of each profile in the data set, repeatability is inherently improved, as well as the precision in the fusion of each line acquired to produce a 3-D data set. The user-friendly interface allows any untrained operator to define a multiple viewpoints scanning trajectory that will be automatically scanned with full registration of the data collected without any external intervention required.

Further work under consideration is the ability to amalgamate the various datasets produced by the multi-modal system into a single dataset, which advertently provides the statistically optimal representation of the scanned scene. Other improvements would be to provide additional information of colouring, texturing, and other essential attributes otherwise not detected by single mode range sensors. Such an enhancement to the multi-modal range sensing system would lead to a more sophisticated model of the captured environment. Finally, the data must be used to create an occupancy model, in order to be used for higher-level robotic applications such as path planning and task completion.

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