Stereo-Vision Based 3D Modeling for Unmanned Ground Vehicles

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ABSTRACT

Instant Scene Modeler (iSM) is a vision system for generating calibrated photo-realistic 3D models of unknown environments quickly using stereo image sequences. Equipped with iSM, Unmanned Ground Vehicles (UGVs) can capture stereo images and create 3D models to be sent back to the base station, while they explore unknown environments. Rapid access to 3D models will increase the operator situational awareness and allow better mission planning and execution, as the models can be visualized from different views and used for relative measurements.

Current military operations of UGVs in urban warfare threats involve the operator hand-sketching the environment from live video feed. iSM eliminates the need for an additional operator as the 3D model is generated automatically. The photo-realism of the models enhances the situational awareness of the mission and the models can also be used for change detection. iSM has been tested on our autonomous vehicle to create photo-realistic 3D models while the rover traverses in unknown environments.

Moreover, a proof-of-concept iSM payload has been mounted on an iRobot PackBot with Wayfarer technology, which is equipped with autonomous urban reconnaissance capabilities. The Wayfarer PackBot UGV uses wheel odometry for localization and builds 2D occupancy grid maps from a laser sensor. While the UGV is following walls and avoiding obstacles, iSM captures and processes images to create photo-realistic 3D models. Experimental results show that iSM can complement Wayfarer PackBot's autonomous navigation in two ways. The photo-realistic 3D models provide better situational awareness than 2D grid maps. Moreover, iSM also recovers the camera motion, also known as the visual odometry. As wheel odometry error grows over time, this can help improve the wheel odometry for better localization.

Keywords: Stereo vision, 3D modeling, Visual odometry, Urban reconnaissance, Unmanned ground vehicles

1. INTRODUCTION

Special Operations Forces (SOF) are often required to enter unknown and potentially hostile environments with no prior knowledge of the layout or possible deployment of hostile forces. Lacking situational awareness prior to entry, the SOF can be taken by surprise by hostile forces, explosives, or other threats. The survivability and effectiveness of the SOF will be greatly enhanced by remotely acquiring knowledge of the environment's layout. The use of Unmanned Ground Vehicles (UGVs) keeps the SOF personnel out of danger and allows them to carry out other critical activities while the UGV is autonomously modeling the environment. With the acquired knowledge of the environment, the SOF will be able to carry out more strategic, targeted and safe operations.

The creation of photo-realistic three-dimensional (3D) calibrated models of observed scenes has been an active research topic for many years. Such 3D models are very useful for both visualization and measurements in the military and other applications such as planetary rovers, security, forensics, mining, archaeology, virtual reality, etc. The capability of creating 3D models automatically and quickly is particularly beneficial. A hand-held device is desirable in many situations as it can be used for scanning by simply moving it freely without any constraint on the motion. It can also be mounted on an UGV to create 3D models while it is exploring the environment.

We have developed the instant Scene Modeler (iSM) that is capable of quickly generating calibrated photo-realistic colour 3D models of unknown environments from a mobile stereo camera [1]. The system works in a hand-held mode where it can process image sequences and automatically stitch them together in 3D with no prior knowledge of the

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environment. The resulting 3D models can be visualized from different views and metric measurements can be performed on the models.

We have implemented a proof-of-concept iSM payload which is mounted on an autonomous UGV to provide photo-realistic 3D modeling and measurements. While the UGV autonomously explores the environment, the iSM payload will generate a photo-realistic 3D model of the environment which can be sent back wirelessly to the base station for mission reconnaissance.

From a remote location, the SOF operator will have near real-time access to the 3D model of the unknown environment. The metrically accurate model may be augmented with multiple forms of additional sensory information, potentially including IR, or thermal imagery. Furthermore, as operationally needed, the iSM 3D modeling payload can be removed from the UGV and operated in a hand-held mode by the SOF personnel.

2. PREVIOUS WORK

3D modeling has been a topic of intensive research for the last few decades. This section presents a brief overview of the main technologies: 3D acquisition, view registration and model construction, and a few 3D modeling systems applicable to UGVs.

2.1 3D Acquisition

The main approaches for depth acquisition include structured light, laser scanning and stereo. The structured light approach uses a projector to illuminate the object with patterns and recovers the 3D shape from a monocular image. It is very effective for scanning objects but do not work well for scanning environments due to their limited range.

Blais [2] has recently reviewed the development of 3D laser imaging for the past 20 years. Auto-synchronous laser scanners can be used for both objects and environments due to their long depth of field and high accuracy at close range. Time-of-flight scanning laser rangefinders measure the time it takes for the light to travel to the object and back. Laser range scanners have to remain stationary during data acquisition and they are large, heavy, and tend to be expensive.

Stereo imaging is a passive technique and can recover the structure of the environment by matching features detected in multiple images of the same scene. It is very computationally intensive as the 3D data is computed from the images. The depth data could be noiser than the other approaches, as it relies on the natural texture on the surface and ambient lighting. Unlike laser scanners, cameras can capture complete images in microseconds, hence they can be used as mobile sensors or operate in dynamic environments. The cost, size, mass and power requirements of stereo cameras are much lower than those of scanning rangefinders.

2.2 View Registration

When multiple scans are obtained, they need to be registered together to build the 3D model. Registration can be carried out with a separate device that tracks the sensor or object position, or by matching the data sets manually or automatically.

The most common algorithm for automatic 3D data registration is Iterative Closest Point (ICP) algorithm [6], which iteratively minimizes the distances between the overlapping regions of two sets of 3D points or surfaces. For vision systems, fiducials can be placed in the scene and the camera pose can be estimated by tracking these markers [7]. However, this involves changes to the environment and it is not possible for some applications. The capability to track natural features in the scene to recover camera motion is much preferred.

2.3 Model Construction

Registered 3D data sets contain redundant overlapping measurements and measurement noise. They contain often too much detail for efficient visualization and manipulation, and they need to be converted to other formats. One approach involves constructing geometrical models, e.g., 3D surfaces or volumes. Triangular meshes that consist of a large number of triangles are often used as they can represent complex surfaces.

The models can be obtained by creating surface meshes from individual views first and then stitching them together [8]. If there is a significant overlap between the individual views, this approach is rather inefficient due to the need for repeated stitching. The volumetric approach is more efficient as the 3D points are accumulated into voxel grid structures first. Only one triangular mesh is created for all the measurements using an iso-surface extraction algorithm, such as the marching cubes [9]. After the triangular mesh is generated, texture images are mapped to provide the photo-realism [10].

2.4 3D Modeling Systems

3D modeling systems have been developed for city scanning or the large-scale reconstruction of urban scenes. Many of them use laser sensors, which can provide accurate 3D measurements directly at long ranges. We will focus on passive camera systems whose advantages have been described above. However, some of those systems require manual operation [11, 12] and hence, it is labour-intensive to create the models. Some other automatic 3D modeling systems simplify the scene as geometric primitives such as planes and polyhedra [13] or use generative building models [14]. Therefore, their application is limited to man-made environments, buildings and city blocks.

Military UGV application requires automatic 3D reconstruction and that the system works in all types of environments including outdoor natural terrains and caves. Pollefeys et al. [15] and Nister [16] presented systems which create 3D surface models from a sequence of images taken with a hand-held video camera. The camera motion is recovered by matching corner features in the image sequence. Dense stereo matching is carried out between the successive frames. The input images are used as surface texture to produce photo-realistic 3D models. However, it requires a long processing time and outputs a scaled version of the original object.

The objective of the ongoing DARPA Urbanscape project is to develop a real-time data collection and processing system for automatic geo-registered 3D reconstruction of urban scenes from video data [17]. Promising results were shown but it is currently far from being real-time. Multiple video streams as well as GPS and INS measurements are collected to reconstruct photo-realistic 3D models and place them in geo-registered coordinates.

3. INSTANT SCENE MODELER

iSM automatically creates 3D models from a mobile hand-held stereo camera. It computes the 3D data, estimates the camera motion and registers successive frames together. The user points the camera at a scene of interest and the system automatically creates a photo-realistic 3D calibrated model within minutes. Part of the processing includes computation of camera motion, which can be used for vehicle localization.

The main hardware components of iSM are a stereo camera and a computer. We currently use a colour Bumblebee stereo camera from Point Grey Research (PGR) [18]. It is a firewire camera that can capture up to 15 frames per second. iSM 3D processing software can run on any PC equipped with a firewire interface.

Figure 1 shows the architecture of the iSM system. Images are captured by the stereo camera and dense stereo disparity is computed using a correlation based algorithm for each pair to obtain 3D data. As with other stereo algorithms, the quality (accuracy, coverage and number of outliers) of the depth data depends on the presence of texture in the images.

The system does not require any external sensors for computing the camera motion as it automatically extracts and tracks natural tie points in the images. We use a high level set of natural visual features called Scale Invariant Feature Transform (SIFT) as the tie points to compute the camera motion. SIFT was developed by Lowe [19] for image feature generation in object recognition applications. The SIFT features are highly distinctive and are invariant to image translation, scaling, rotation, and partially invariant to illumination changes and to affine or 3D projections. These characteristics make them suitable as landmarks for robust matching when the cameras are moving around in an environment. Previous approaches to feature detection, such as the widely used Harris corner detector [20], are sensitive to the scale of an image and therefore are less suitable for building feature databases that can be matched from a range of camera positions.

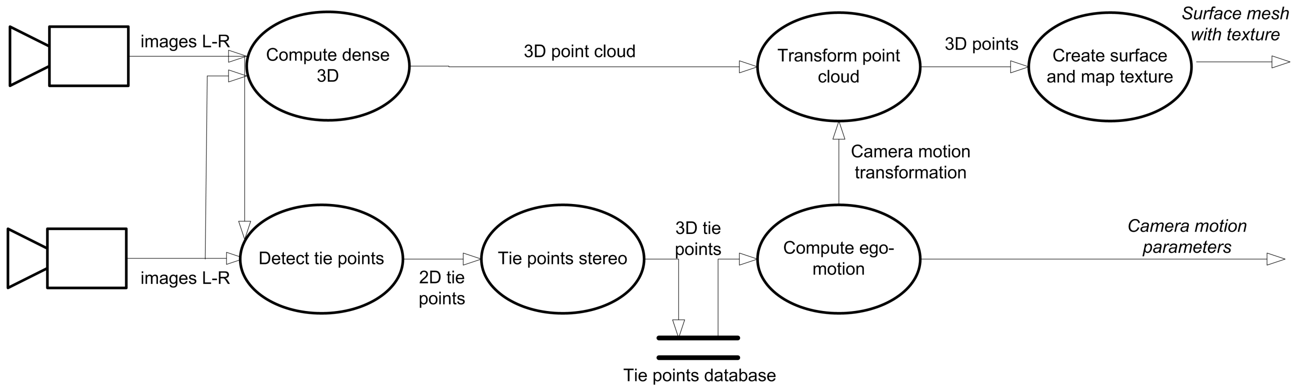

Figure 1: iSM system architecture

Using the known stereo camera geometry, the SIFT features in the left and right images are matched using the following criteria: epipolar constraint, disparity constraint, orientation constraint, scale constraint, local feature vector constraint and unique match constraint [21]. The subpixel disparity for each matched feature is also computed. Typically, we obtain hundreds of SIFT 3D features.

We recover the 6 degrees of freedom (dof) camera ego-motion when the camera moves freely in the hand-held mode. We employ a Simultaneous Localization And Mapping (SLAM) approach that uses the SIFT 3D features to localize and simultaneously build a database map [21]. Instead of frame to frame matching, we match the SIFT features at each frame with the database to reduce error accumulation. Olson et al. [22] reported a 27.7% reduction in rover navigation error when multi-frame tracking is used, rather than considering each pair of frames separately.

As the SIFT features are highly distinctive, they can be matched with very few false matches. This allows finding the camera movement that brings each projected SIFT feature into the best alignment with the matching feature in the database. A weighted least squares procedure is carried out taking into account the feature uncertainty. Features with large least square errors are discarded as outliers.

3D data is computed in the camera reference frame and is transformed using the camera pose estimated for this frame. Typically, the initial camera pose is used as the reference.

Using all 3D points obtained from the stereo processing is not efficient as there are a lot of redundant measurements, and the data may contain noise and missing regions. Representing 3D data as a triangular mesh reduces the amount of data when multiple sets of 3D points are combined. Furthermore, creating surface meshes fills up small holes and eliminates outliers, resulting in smoother and more realistic reconstructions.

To generate triangular meshes as 3D models, we employ a voxel-based method [9], which accumulates 3D points into voxels at each frame with their associated normals. It creates a mesh using all the 3D points, fills up holes and works well for data with significant overlap. It takes a few seconds to construct the triangular mesh at the end, which is dependent on the data size and the voxel resolution.

The photo-realistic appearance of the reconstructed scene is created by mapping camera images as texture. Such surfaces are more visually appealing and easier to interpret as they provide additional surface details. Colour images from the stereo camera are used for texture mapping. As each triangle may be observed in multiple images, the algorithm needs to select a texture image for each triangle. To reduce the appearance of seam lines between triangles, we select the texture images that can cover the most number of triangles. The model will therefore need the minimal number of texture images, and hence this allows faster model loading and lower storage requirement.

4. EXPERIMENTAL RESULTS

4.1 iSM Hand-held Mode

Field tests in various environments have been carried out with promising results. In one of the experiments, we modeled a facade of a house. The camera was moved freely in hand-held mode pointing at different portions of the house and about 30 seconds of images at 640x480 resolution were captured. Figure 2 shows two input images from the house sequence. The system then processed these images and created a photo-realistic 3D model automatically in around 5 minutes on a Pentium IV 2.4 GHz laptop.

The output 3D model is stored in the VRML (Virtual Reality Modeling Language) format. The user can navigate in the 3D model, and view it from any direction and distance. Figure 3 shows two views of the 3D model. We can see that iSM can reconstruct the overall 3D model by integrating all the input images, each of which captured with a limited field of view.

More advanced visualization and user interaction is provided in our visualization GUI (Graphical User Interface). As the 3D model is calibrated, the user can perform measurements (such as distance, angle, area) on the 3D model and the user can also annotate the model, as shown in Figure 4 (left). The camera trajectory recovered from the ego-motion estimation can be visualized, as shown in Figure 4 (right). Moreover, the GUI also provides other features such as movie creation using trajectories defined with keyframes, model alignment and the export of 3D models into DXF format.

Figure 2 Two images selected from the house sequence

Figure 3 Two views of the 3D model generated by iSM for the house scene

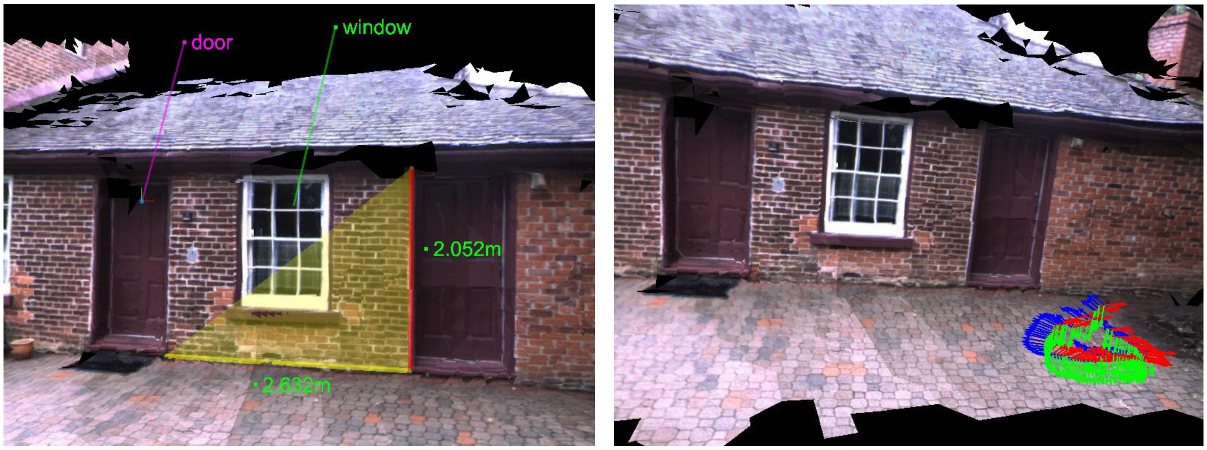

Figure 4 iSM visualization GUI showing the annotation and measurement (left) and the recovered camera trajectory (right)

4.2 iSM on MDA Autonomous Vehicle

For autonomous vehicles and planetary rovers, the creation of 3D terrain models of the environment is useful for visualization and path planning [23]. Apart from the 3D model, iSM also computes the camera motion (also known as the visual odometry) which allows the vehicles to localize themselves more accurately, as wheel odometry is prone to slippages over time. Apart from using iSM in the hand-held mode, it can be deployed on both tele-operated and autonomous vehicles to create 3D models while the vehicles traverse in unknown environments.

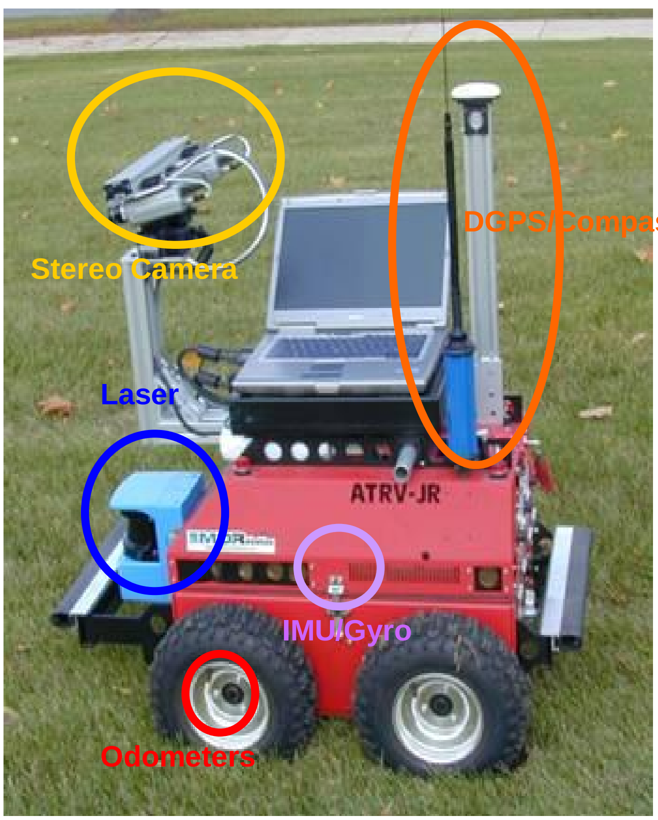

Figure 5 MDA Autonomous Vehicle

The MDA Autonomous Vehicle testbed is shown in Figure 5. The chassis of this rover is an iRobot ATRVJr with a custom vision system. The stereo camera was constructed using a pair of Sony DFW-X700 cameras, mounted on a rigid bar and affixed to a pan-tilt unit. The camera field of view is approximately 45 degrees horizontal and 35 degrees vertical. There are currently two computers on board, a dual Pentium III 1 GHz with 1 GB of RAM (inside the red box) and a dedicated vision computer consisting of a Pentium M 1.8 GHz with 1 GB of RAM. The vision computer also houses our hardware accelerated vision processing boards, a Tyzx DeepSea2 [24] for dense stereo calculations and an AlphaData ADM-XRC board with a Virtex II Xilinx FPGA running our implementation of SIFT feature extraction [23]. There are various other sensors onboard as well: sonar rangefinders, SICK laser rangefinder, DGPS, compass, inertial measurement unit and inclinometer.

iSM has been tested on this testbed traversing at a desert in Nevada. Figure 6 (left) shows an image from a sequence captured by the vehicle during traversal of 40m and Figure 6 (right) shows the reconstructed 3D terrain model with a virtual vehicle inserted for visualization. Figure 7 shows the recovered camera trajectory without using wheel odometry. Despite the jerky motion, iSM is able to compute the camera motion and create a photo-realistic 3D model from the input stereo image sequence.

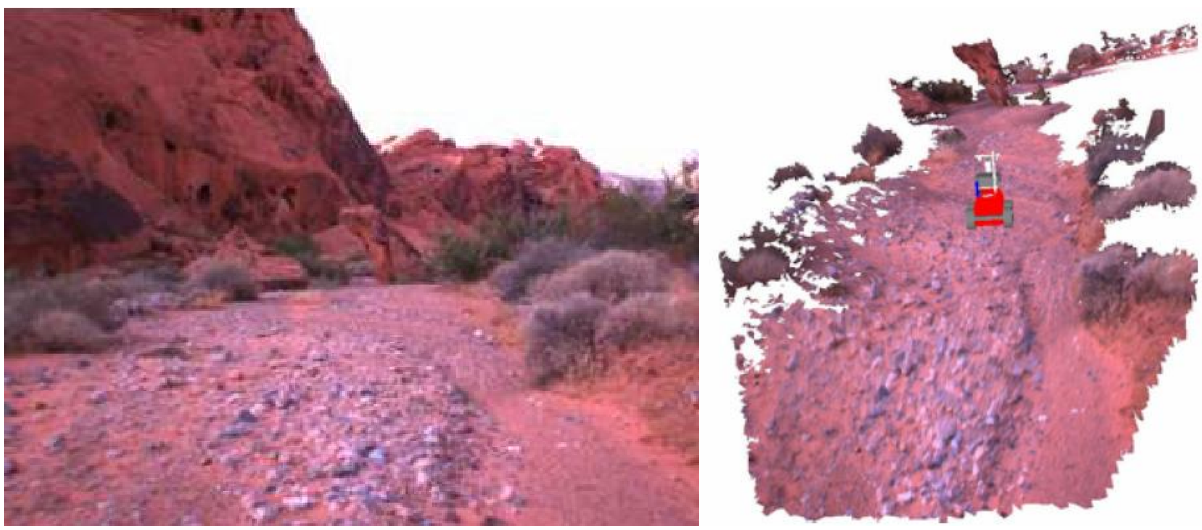

Figure 6: An image from a sequence taken by the MDA Autonomous Vehicle at a desert in Nevada (left) and the reconstructed 3D model with the vehicle model inserted for visualization (right).

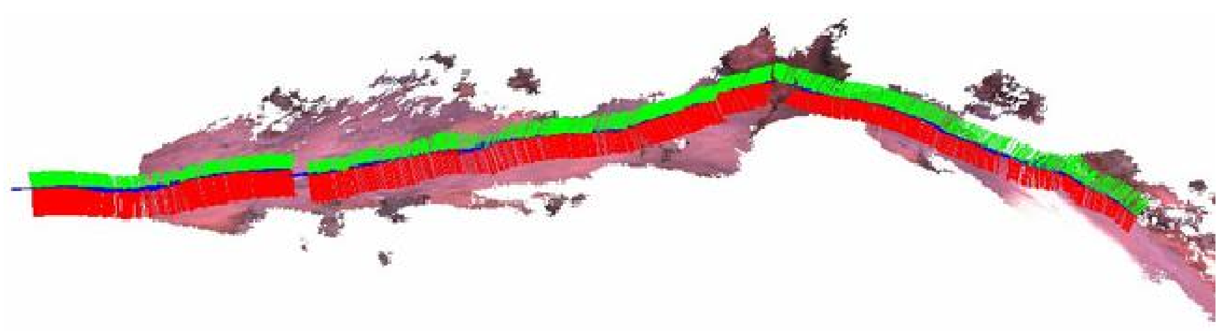

Figure 7 Camera trajectory computed by iSM for the Nevada dataset

5. WAYFARER PACKBOT

We have also implemented a proof-of-concept iSM payload on PackBot, a rugged, man-portable military mobile robot produced by iRobot Corporation [25].

5.1 iRobot PackBot

iRobot PackBot is a highly-robust, all-weather, all-terrain, man-portable UGV platform, equipped with two main treads for locomotion and two articulated flippers with treads to climb over obstacles. PackBot can travel at sustained speeds of up to 4.5 mph. It is 27 inches long, 16 inches wide, and 7 inches tall, and weighs 40 pounds. All electronics are enclosed in a compact, hardened enclosure, including a 700 MHz mobile Pentium III with 256 MB SDRAM, a 300 MB compact flash memory storage device, and a 2.4 GHz 802.11b radio Ethernet. Each PackBot can withstand a 400G impact, the equivalent of being dropped from a second storey window onto concrete. Each PackBot is also waterproof to 3 metres. Three modular payloads fit into the rear payload bay. Each payload connector provides power, Ethernet, and USB connections from the PackBot to the payload module for highly-flexible mission capability.

PackBot is at home in both wilderness and urban environments, outdoors and indoors. In the wilderness, PackBot can drive through fields and woods, over rocks, sand, and gravel, and through water and mud. In the city, PackBot can drive on asphalt and concrete, climb over curbs, and climb up and down stairs while carrying a payload. PackBot can also climb up, down, and across surfaces that are inclined up to 60 degrees. In addition, PackBot can climb up and down inclines of up to 55 degrees, and across inclines of 45 degrees, while carrying a 22.5 pound payload.

5.2 Wayfarer PackBot

While the PackBot is tele-operated, autonomous urban navigation capabilities have been developed in the Wayfarer project [26]. A modular navigation payload has been developed that incorporates a 3D stereo vision system, a 360-degree planar LIDAR, GPS, INS, compass, and odometry. This payload can be attached to any PackBot to provide the robot with the capability to perform autonomous urban reconnaissance missions. The PackBot with Wayfarer technology will be able to scout unknown territory and send back occupancy maps along with video image sequences.

The Wayfarer navigation payload includes software components for obstacle avoidance, building perimeter and urban street following, and map-building. The obstacle avoidance system enables the PackBot to avoid collisions with a wide range of obstacles in both outdoor and indoor environments. This system combines 360-degree planar LIDAR range data with 3D obstacle detection using stereo vision. A real-time Hough transform is used to detect linear features in the range data that correspond to building walls and street orientations. The LIDAR range data builds an occupancy grid map of the robot's surroundings in real-time. Data is transmitted via UDP over wireless Ethernet to an OpenGL-based Operator Control Unit (OCU) that displays this information graphically and in real-time.

5.3 iSM on Wayfarer PackBot

We have mounted a proof-of-concept iSM payload on the Wayfarer PackBot. The payload consisted of a stereo camera and a compact laptop computer (Toshiba Libretto with 1.1 GHz processor). There was no inter-communication between the iSM payload computer and the PackBot computer. The stereo images were captured and processed on the payload computer on top of the PackBot. A separate control computer was used for communication with the iSM payload and for 3D model visualization.

Figure 8 shows the integration of the Wayfarer PackBot UGV with the iSM 3D modeling payload. The stereo camera with the MDA logo belonged to the iSM payload while the second one was part of Wayfarer's sensor package. The iSM payload camera was pointed slightly to the right side during the test runs, so that it could get a better view of the building for 3D reconstruction, rather than capturing the road ahead only.

Due to the limited payload computing resources and the relatively high speed of Wayfarer PackBot, the images were captured with resolution of 320x240 pixels and at 7Hz. During a test run, the Wayfarer PackBot autonomously navigated around the building in the perimeter following mode while iSM was capturing images. At the end of the test run, iSM started processing the stereo images and created a photo-realistic 3D model.

Figure 9 shows selected images captured by the iSM payload for test run 1. The traverse was around 20m and took around 1 minute. The processing time was under 5 minutes on the payload computer. Screenshots of the resulting 3D model from different views are shown in Figure 10, together with the recovered camera trajectory.

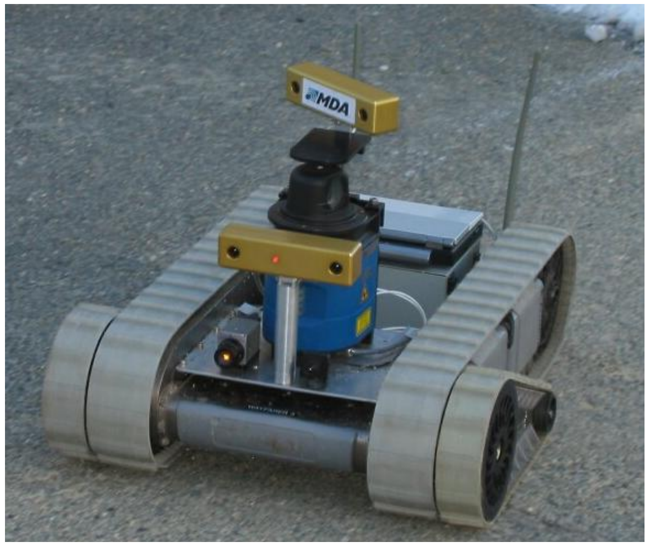

Figure 8: A proof-of-concept iSM 3D modeling payload mounted on the iRobot PackBot with Wayfarer technology. The payload consists of a stereo camera (with the MDA logo) and a compact laptop at the back

Figure 9 Selected images from test run 1

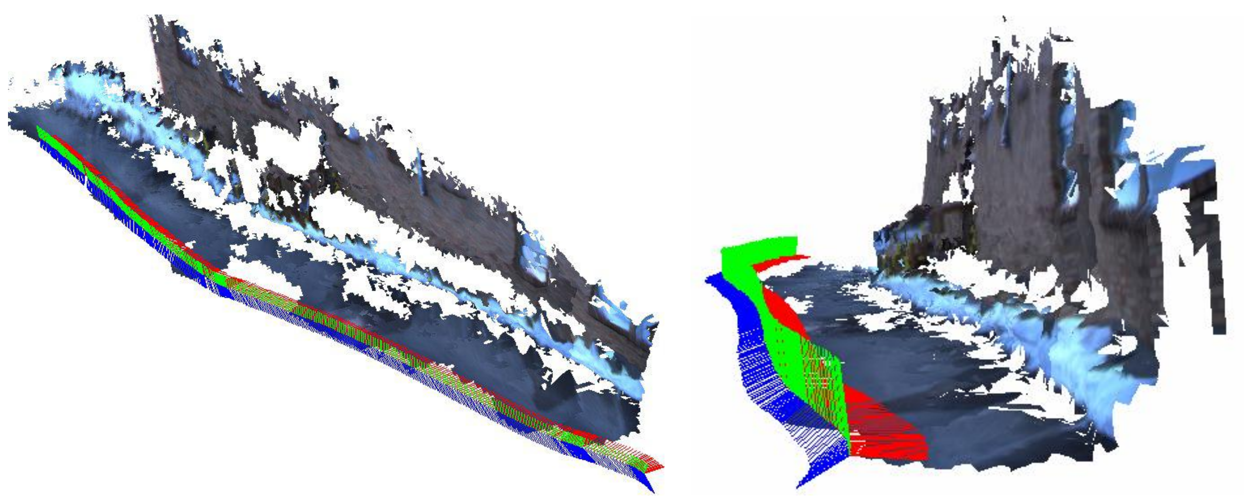

Figure 10 Different views of the resulting 3D models with recovered trajectory highlighted for test run 1

Figure 11 Selected images from test run 2

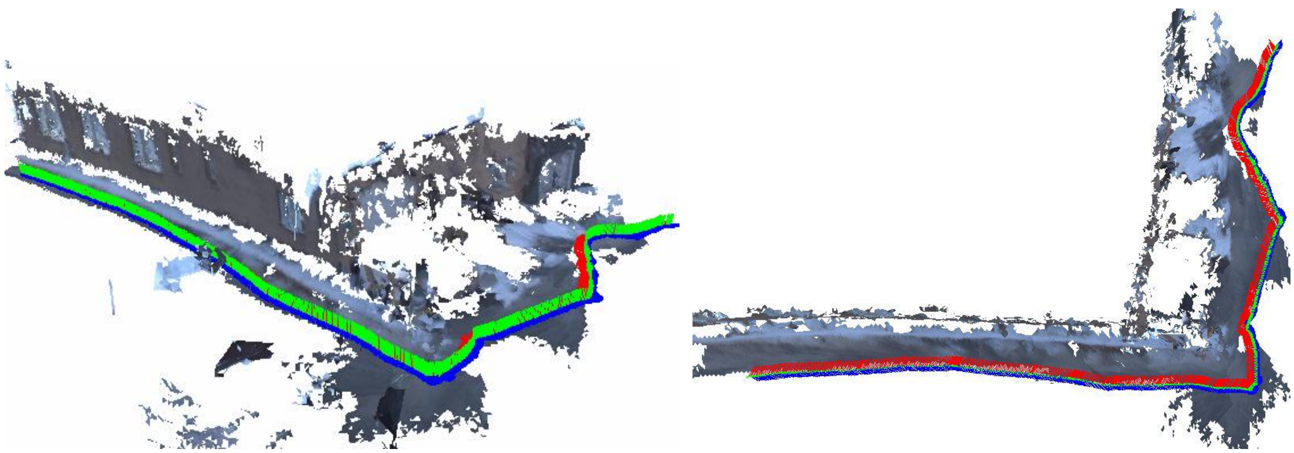

Figure 12 Different views of the resulting 3D models with recovered trajectory highlighted for test run 2

Another test was carried out in which the Wayfarer PackBot turns around the corner of the building. Figure 11 shows some input images captured by the iSM payload for test run 2. Screenshots of the resulting 3D model from different views are shown in Figure 12. The total traverse is around 40m and takes around 3 minutes. The processing time is less than 10 minutes.

Key capabilities of a mobile robot system are simultaneous localization and building maps of visited environments. Experimental results show that the iSM payload can complement the Wayfarer PackBot in both aspects. While the Wayfarer PackBot is autonomously following the building perimeters and avoiding obstacles, it builds 2D occupancy grid maps from the laser sensor, whereas iSM is capable of creating photo-realistic 3D models. The photo-realistic 3D models provide better situational awareness than 2D occupancy grid maps.

The Wayfarer PackBot uses wheel odometry for localization and to build the occupancy grid map. As wheel odometry is prone to error, an additional INS/GPS unit is used recently to improve localization [27]. iSM can also recover the camera motion, also known as the visual odometry, which can help improve the wheel odometry for better localization.

However, as the iSM processing is not done in real-time and there is no communication between iSM and PackBot computers, the PackBot cannot currently use the visual odometry information produced by iSM.

iSM requires texture features in the environment for both camera motion estimation and 3D coverage. Missing regions in the 3D model indicate insufficient texture in the scene for dense stereo matching. The rotational speed of the Wayfarer PackBot can cause problems to iSM as when it rotates very quickly, there may not be sufficient overlap between frames to track the features. As the motion estimation error accumulates over long sequences, it can be noticed that the building wall looks slightly curved in Figure 12.

6. CONCLUSIONS

In this paper, we have presented a 3D modeling system, the instant Scene Modeler (iSM). iSM uses a hand-held stereo camera for recording images and a laptop for acquisition and processing. It creates photo-realistic 3D calibrated models of environments automatically (no user interaction) within minutes. As the effectiveness of the SOF will be greatly enhanced by having a layout of the environment, current military operations of UGVs in urban warfare threats involve the operator hand-sketching the environment from live video feed. iSM eliminates the need for an additional operator as the 3D model is generated automatically.

A proof-of-concept iSM payload has been integrated on two mobile robots from iRobot: ATRVJr, a research robot, and Wayfarer PackBot UGV, a rugged military robot equipped with autonomous navigation capabilities. Experimental results are promising and they show that iSM can complement Wayfarer PackBot's autonomous navigation in two ways. The photo-realistic 3D models created by iSM will enhance the situational awareness of the mission and the models can also be used for change detection. The visual odometry recovered by iSM can be fused with the wheel odometry for better UGV localization.

The SOF situational awareness before entering an unknown environment will be greatly enhanced through the acquisition of a high-fidelity, photo-realistic 3D model. The safety of the SOF will be increased through the remote operation and monitoring from a secure stand-off location. As a result, overall mission effectiveness, success, and safety will be greatly increased.

Future work includes better integration of the iSM payload with the PackBot. This will allow the control of the iSM payload from PackBot's OCU, and also the transfer of the reconstructed 3D models via PackBot wireless link to the OCU for visualization. Moreover, inter-communication between the payload and the PackBot will allow iSM to make use of PackBot wheel odometry and improve it robustly with visual information. iSM processing can be optimized to provide online visual odometry by means of software and hardware acceleration. Furthermore, better dense stereo algorithms [28] can be investigated to improve the 3D coverage of the models. Backward correction techniques for map building can be considered to improve the model correctness for long sequences [29].

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